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CRITICAL AREAS

SATELLITE POWER SYSTEMS CONCEPTS

A report from the Satellite Power Team to the Assistant Administrator
for Energy Programs, National Aeronautics and Space Administration.

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I. SUMMARY

Critical Areas have been defined and discussed in the various areas pertinent to satellite power systems. The presentation is grouped into five areas (General, Space Systems, Solar Energy Conversion, Microwave Systems, and Environment/Ecology) with a sixth area (Power Relay) considered separately in an appendix. Areas for Future Consideration as critical areas are discussed in a second appendix.

The most critical areas from the combined points of view of being a significant, difficult-to-project, cost item and having no ready solution in work or even firmly in mind are:

A.3. System Analysis and Engineering

No really complete system analysis has ever been performed on any satellite power system concept. A fairly large effort is required to provide means for a complete understanding of the SPS, its elements, and operational aspects. The SPS consists of an unprecedented number of systems, subsystems, and operational elements with complex interrelations. A complete, step-by-step presentation of the totality of interrelated SPS systems and the associated operations is required for a valid feasibility assessment.

B.2. Transfer Vehicle

Many of the earlier concepts have been found deficient in one way or another under further investigations. At the present time there is no proven viable concept for the transfer vehicles. A large, multi-faceted effort is necessary to define the requirements, perform transfer vehicle/satellite structural design trade offs, generate preliminary definition of several candidate transfer vehicles, and to evaluate these candidates. Technology development is probably required for the thrusters, power conditioners, and power sources.

B.3. Large Space Structures

This may well be the most critical area. Detailed requirements by the satellite power system on the structure are largely undefined. It will represent

a significant part of the total costs and at the present time no viable design exists even in preliminary form. Several areas have begun to be investigated but much more is required. The requirements of the structure on the rest of the satellite systems are largely unknown. Subareas of (a) Materials, (b) Structure, Assembly, and Fabrication, (c) Thermal Control, (d) Attitude Control and Stationkeeping, and (e) Operations, Logistics, and Support Modules must be probed in depth before confident cost projections can be made.

Other areas are as critical from the cost-effect or projection point of view, but, either have solutions already underway or preliminary plans in mind.

A. 1. Strong, Central Coordination

Present plans for the Satellite Power Team should satisfy this area. New efforts are probably not required.

A. 2. Economic Commonality

The necessary procedures and guidelines for all future efforts to ensure economic comparability are expected to be largely provided by the present MSFC/ECON effort. A small scale followon may be necessary to complete the objectives.

A. 4. Utility Interface

Assumptions have been made in past studies with respect to the nature of the utility interface. These were probably reasonable but additional definition efforts to illuminate all the requirements (of the SPS on the utility and of the utility on the SPS) and to involve the utility industry to a small extent in the early studies of SPS feasibility are required.

B. 1. Heavy Lift Launch Vehicle

A target cost of \$44. /kg to low Earth orbit is seen as an ambitious but possible goal for an annual launch rate as high as would be required. Some expansion and extension of existing studies should accomplish many of the objectives with a few additional efforts required.

C. 1. Photovoltaic Conversion

Parameters and requirements for solar cells given by early studies are seen as extremely optimistic and probably not attainable without an awesome breakthrough. Efforts must be undertaken to define reasonable goals and risks for solar cells. Devices other than single crystal silicon must be investigated for promising potential. Maximum use of efforts for terrestrial applications should be made.

C. 2. Thermal Conversion

Studies are required to establish cost and mass goals for the concentration and absorption of solar energy and for the thermal generator systems. Hardware verification should follow preliminary, conceptual efforts. The most promising system concepts for thermal to electric conversion should be selected for concentrated effort.

C. 3. a. High Voltage - Plasma Interactions

Further theoretical studies and experimental verification are necessary to define the extent of any adverse interactions and to indicate promising approaches to avoid these difficulties. Eventual experiments in space are probably called for.

C. 3. b. Power Processing for Photovoltaic Power Generation

C. 3. c. Power Processing for AC Generator

Efforts are required for both of these areas to determine present capabilities and to set reasonable goals for the efficiency, mass, lifetime, and cost of these subsystems. Identification of anticipated problems would indicate where to concentrate the follow on effort.

D. 1. DC-RF Conversion

Preliminary study efforts have been performed in this area. It is now time to build some of the devices to verify the predictions and measure the important parameters directly. With this data optimization and tradeoffs can be made and requirements on the rest of the systems defined.

D. 2. Transmission Phase Control

Early verification of the adequacy of a preliminary scheme is required.

The system operational characteristics need to be determined by study and verified by experimentation. Operational experience must be gained with respect to system stability and security.

D. 3. Waveguide

The waveguide, being a potentially lossy component, must be understood early as it will affect other systems directly. The operating environment and interfaces must be determined and any materials questions resolved. Tradeoffs and design should be followed by hardware fabrication. Early Space Shuttle experimentation is probably also required in the fabrication and assembly of the waveguide.

D. 4. RF-DC Conversion

At the present time this area is in reasonably good shape. Further efforts are required to determine detailed subsystem operational interfaces and environmental conditions as well as efforts to increase the performance of existing, preliminary designs.

D. 5. Microwave Beam Propagation - Technical Considerations

A preliminary study is required to define and quantify the propagation path elements. Ground based experimentation should be followed with space based experimentation to verify the acceptability of the RF system design.

D. 6. Radio Frequency Interference

Each potential DC-RF converter must be examined (theoretically and experimentally) with respect to its performance and spectrum. Tradeoffs will have to be made to determine impacts on SPS and other spectrum users. National and International regulatory agencies should be worked with to arrive at an acceptable solution.

E. 1. Biological Effects of Microwave Beam

The effects of the microwave beam on the plant and animal life within it must be understood. A three-pronged effort is envisioned commencing with preliminary studies to understand the effects and interactions. Dosimetry to monitor the dose must be developed and a research facility to perform the necessary experimentation may be required if existing facilities cannot be found.

E. 2. Transportation System Pollutants

Each vehicle study effort must generate the required data on emissions. A study to assess impacts and to provide trade off data for each candidate vehicle is required with a following experimental verification effort. Atmospheric modeling accuracy must be increased.

E. 3. Microwave Beam Propagation - Environmental Considerations

Area D. 5. efforts will contribute to this area in the initial years. Followon studies, as identified in these early efforts, should be performed to assess the environmental impacts.

II. INTRODUCTION

This is a report from the Satellite Power Team to the Assistant Administrator for Energy Programs in the National Aeronautics and Space Administration. It does not necessarily represent the viewpoint of the NASA. The objectives of this report are:

1. To identify and describe the critical areas of potential satellite power systems.
2. To formulate the objectives of the required efforts to resolve the areas.
3. To present a preliminary recommended approach and preliminary program estimates for use in program planning efforts to follow.

(These estimates will be very preliminary and are expected to change significantly in the program planning efforts when all is put together and overlap of areas is recognized.)

The "Preliminary Technology Assessment" (Report from the Satellite Power Team to the Assistant Administrator for Energy Programs, February 1975) concludes that there is a reasonable chance of satellite power systems being economically competitive. However, this analysis is based, admittedly, on some very "soft" numbers and projections. The first order of business is to make better, more accurate economic projections possible, so that they can be used as a basis for decisions regarding longer term program commitments by the NASA. Thus our present program commitment is to a near-term, "get smart" program. This is envisioned as a 3-5 year plan emphasizing those elements that limit our ability to make accurate cost forecasts.

For the purposes of this report a Critical Area is defined as any area (could be a system, a component, an idea, a management requirement, etc.) that presently constrains our ability to project the economic viability of satellite power systems. This may be due to technical, economic, emotional, or other grounds.

The information contained in the "Preliminary Technology Assessment" forms the systems basis for starting this report. Subsystem details have

been brought up to the present state-of-the-art as best as possible. Two comparable satellite power systems (one a photovoltaic converter, the other a solar concentrator/Brayton turbogenerator) were examined in the "Preliminary Technology Assessment" with respect to costs. Important parameters of the two systems follow. For more details, see the "Preliminary Technology Assessment."

The photovoltaic system assumed 18% efficient, 50 um thick cells with an assembled array cost of \$0.22/w. The microwave system consisted of 90% efficient amplitrans and a 90% efficient slotted waveguide phased array, 1 km in diameter. The ground receiver was an expanse of rectenna elements to receive and convert the microwaves to dc. Total orbiting mass was somewhat over 20×10^6 kg. Transportation costs of \$44./kg to LEO and \$11./kg to GSO were assumed, and a blanket cost of \$630 M was taken for assembly and flight operations. The plant delivered 8.3×10^{10} kwh/yr. (10 GW at 95% plant factor) at a specific capital cost of \$1012/kw and bus bar costs of 25 mil/kwh or 32 mil/kwh (2 or 5 year construction times respectively).

The Brayton turbogenerator system replaces the solar cells with a system for concentrating and absorbing the energy to drive a Brayton cycle turbogenerator. Concentration/Absorption efficiency of 54% was used with a Brayton engine/generator efficiency of 38% for an overall efficiency of 21%. Total orbiting mass was somewhat over 35×10^6 kg. The same parameters were used for other systems as were used for the photovoltaic system. The plant produced 7.9×10^{10} kwh/yr (10 GW at 90% plant factor) at a specific capital cost of \$928/kw and bus bar costs of 24 mil/kwh or 31 mil/kwh (2 or 5 year construction).

The cost projections for both of these systems were based on very incomplete data and optimistic assumptions. Our task now is to examine these and make them as realistic as possible.

In the body of the report that follows each critical area discussion stands largely on its own. In spite of obvious interrelationships and interdependences

each area has been described in a manner that should be understandable by itself. In addition the format is intended to make clear to those carrying out the parts of the forthcoming program what the exact objectives of that portion are and how they fit into the whole program.

- Background briefly places each area in its context. Requirements (by the overall system) on this area are given quantitatively or qualitatively to the extent that they are known.
- Criticality describes why this area is considered critical.
- Objectives of Required Efforts list the objectives that efforts attempting to satisfy this area (for the near-term, "get smart" program) must meet.
- Recommended Approach is a preliminary concept that appears to be capable of meeting the objectives. It is intended as guidance to the program planning effort and not as guidance to those carrying out the program elements.
- Program Estimates is likewise a section intended for use in the program planning efforts.

Power Relay Satellites for transmission of power has been handled separately and is discussed in Appendix 1. The main body of the report deals specifically with satellite power generation systems; although it incidentally includes the vast majority of considerations for power relay satellites as well. Specific consideration of relay satellites are dealt with in this appendix so that the generation/transmission aspects will not be confused.

The Satellite Power Team, serving in a consulting capacity to NASA's Office of Energy Programs, has prepared this report. The team is composed of:

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 Simon Manson, NASA Hqs
 Hubert Davis, JSC
 Luther Slifer, GSFC
 James Ward, LeRC
 Richard Dickinson, JPL
 Bernard Newsom, ARC
 Georg von Tiesenhausen, MSFC

Each member has had a hand in all sections, but prime responsibilities for the critical areas sections were:

Lenoir - Final Editor

von Tiesenhausen - General

Davis - Space Systems

Slifer - Photovoltaic Conversion

Ward - Thermal Conversion and Distribution

Dickinson - Microwave Systems

Newsom - Environment/Ecology

It should be emphasized that the entirety of the efforts discussed in this report would not form a complete program for implementation of satellite power systems. That is not the intent of this report. Examining those areas that adversely affect our ability to make cost projections is our sole aim. Other efforts will follow, as appropriate, in the future.

Finally, let us say that this report is not intended to be final in any way. New areas will be continually defined (see Appendix 2) as we go along and old areas will continually be updated. The program and planning is expected to be highly dynamic in this regard.

III. CRITICAL AREAS

A. GENERAL

A.1 STRONG, CENTRAL COORDINATION

Criticality

In the forthcoming "get smart" effort, a highly dynamic program will be called for to allow the Agency to consider the options and to make the decisions necessary in the future for Satellite Power Systems. Many of the subsystem efforts are closely interrelated. To assure completeness and adherence of the efforts strong, central coordination of the overall efforts is required.

Objectives of Required Efforts

1. Preparation of continuing research and technical assessments.
2. Definition of critical areas.
3. Prioritization of critical areas and preparation of a dynamic program plan to accomplish the necessary objectives to resolve the critical area problems.
4. Continuing assessment of the progress of the program and modifications to the program plan as developments indicate.
5. Represent NASA and the Office of Energy Programs to outside organizations as requested.

Recommended Approach

The Satellite Power Team has been constituted to accomplish the required objectives. The functioning of the Team should be sufficient for this area with the possible addition of a small-scale support contract to help the Team in its efforts.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Plans
 - Preliminary Technology Assessment - complete March 1975; update semiannually.
 - Critical Areas - July 1975; update 12/75, 6/76
 - Program Plan - September 1975; update 9/76
 - Program Assessment - Quarterly at Satellite Power Team meetings
 - Final Report - October 1976; Satellite Power Team tenure complete; decision on how to proceed required.

STRONG, CENTRAL COORDINATION (A.1)

Preliminary Program Estimates

Cost and Schedule

TASK	FY	76	77
Satellite Power Team Travel		50K	50K(?)
Support Contract		50-100K	50-100K(?)

A.2 ECONOMIC COMMONALITY

Criticality

In order for equitable comparisons to be made between competitive systems the economic studies must be structured as equal capability analyses based on common assumptions and presented in comparable forms. This will avoid the problem of some existing studies that are difficult to compare due to system capability differences, different economic assumptions, etc.

Objectives of Required Effort

1. Net present value analysis should be adopted as the major analytical method for comparison of the satellite power systems and terrestrial alternatives. The output of this analysis should display life cycle cash flows both in constant, year-of-estimate dollars and in discounted to year-of-estimate dollars.
2. Other data should be developed that would allow comparisons with data used by the FPC, ERDA, EPRI, utility industries, and others. This data should present total unit cost (mil/kwh) of energy as well as the portions of this total attributable to capital investment, fuel, and operations and maintenance. In addition, total capital investment costs (\$/kw) should be presented. Research and development costs should be estimated separately to maintain their amortization as an option.
3. All cost, economic, and technical assumptions, estimating methodologies and techniques should be clearly stated. An analysis of the risk due to uncertainties in the cost estimates should be made.
4. The above work should insure an equitable comparison of all systems with regard to direct dollar costs and benefits. However, decisions may involve other costs, frequently referred to as social costs that are not borne by the decision maker and therefore do not enter quantitatively into the cost. But these costs are borne by society and certainly should be addressed in a qualitative manner. These social costs include ecological effects, risks to the population, and other social effects. Social benefits might also be realized, as in the area of a decreased environmental burden due to the lessened demand

for conventional energy sources afforded by a satellite power system.

Recommended Approach

The present ECON and JPL efforts should continue to deal with these objectives. A contracted follow-on effort (not necessarily the same contractor) should complete the fulfillment of the above objectives, with the depth and scope depending on the degree to which the present efforts meet the requirements. An alternative would be a task of the support contractor to the Satellite Power Team. The final documentation of the analytic method and format to be used should be a part of all future efforts to ensure compliance.

Preliminary Program Estimates

The present ECON and JPL efforts should have completed any contributions to this area by early fall, 1975. A follow-on effort (if not done as support to the SPT) would probably require six months and \$50K. Complete by early spring 1976 with significant results by January 1, 1976.

⊙ Cost and Schedule (see chart)

ECONOMIC COMMONALITY (A.2)

Preliminary Program Estimates

Cost and Schedule

TASKS	FY	1	2
1. Ongoing ECON and JPL Studies		←→	
2. Net Present Value Economic Analysis for SPS			\$50K ←→

A.3 SYSTEM ANALYSIS AND ENGINEERING

Criticality

The definition of required SPS assessment efforts within a comprehensive and optimum program requires understanding of the sensitivities of numerous parameters of the system so that technical efforts can be applied most effectively. Guidelines are needed to perform the proper trade-offs and optimizations in order to arrive at valid requirements and at the technical feasibility and associated cost of the total program. The need for proper direction, coordination and definition of the required technology development efforts in the SPS subsystem and component areas require a thorough understanding of the total system, its requirements and operation, and thus makes this a very critical area. System analysis and engineering efforts are the key essentials that will provide this understanding. More specifically, efforts in this area will provide information necessary for:

A. The selection of a technically and economically feasible configuration, consisting of four major interdependent elements:

- (1) Transportation Systems
- (2) Orbital Power Station
- (3) Ground Receiving Station
- (4) Assembly and Maintenance Operations

B. The definition of critical technology development requirements by establishing the technology categories involved, a rationale for priorities and by defining the specific technology development tasks, milestones, decision points and resources required to resolve the criticalities.

C. The identification of the appropriate key intermediate milestones that would serve as decision points leading toward an operational SPS by verifying critical technology development results through experimentation and demonstration.

Objectives of Required Efforts

General - The prime objective is to provide means for a complete understanding of the SPS, its elements and operational aspects. The total SPS consists of an unprecedented number of systems, subsystems, and operational elements with

complex interrelations. A complete, step-by-step presentation of the totality of interrelated SPS systems and the associated operations and activities is required for a valid feasibility assessment. Therefore, care has to be taken that an overall systems analysis and engineering and cost optimization effort remains a manageable task.

The total problem consisting of the many elements of the required space transportation systems, the power satellite itself, the ground system elements, and the operational activities must be broken down into manageable entities. The early definition of the most sensitive parameters within each entity, and those that relate to or are interdependent on several categories is fundamental to organizing, understanding, and accomplishing such a task. The optimization process, then, must proceed by iteration through increasing levels of depth as more subsystem technology information and options become available in order to clearly show all areas that need concentrated development efforts.

Particular emphasis in the description of the objectives of required efforts is given here to the Orbital Power Station over the other elements (transportation, ground, operations) because the Orbital Power Station Systems determine to a very large extent the requirements imposed on the other three systems.

Specific Objectives - The following objectives have to be defined and implemented in order to provide the facts and data needed to perform sensitivity and economic analyses and trade-offs between critical parameters and to initiate and sustain a logical and well justified approach to the resolution of the SPS critical areas:

1. Define total SPS system requirements as the basis for system and subsystem configurations that will respond to these requirements. A complete and comprehensive definition of requirements prior to initiation of the program has the greatest potential for achieving the most economical program approach. Requirements have to be realistic; too ambitious requirements result in high cost or failure.
2. Establish basic reference or comparison systems that respond to the interdependent transportation, orbital, ground, and operations requirements

using the best design criteria available from all previous efforts.

3. Define responsible candidate system options that fulfill the requirements, such as:

- (1) Single and multistage transport vehicles, chemical and/or electric propulsion, manned and unmanned.
- (2) Photovoltaic or thermal energy conversion.
- (3) Various ground receiver station options.
- (4) Support operations options.

These representative options must be supplemented with other options recognized during the analytical processes.

4. Define ^{ve}responsible candidate subsystem options based on the systems requirements.
5. Define a total work breakdown structure to the subsystem level which interrelates the elements of work required to be accomplished to achieve the objectives. This serves as a common denominator for structuring technical development, scheduling, and costing efforts both in terms of planning and of subsequent execution of this work. Based on this structure, develop economic and cost data in conformance with the methods developed under "Economic Commonality".
6. Determine system and subsystem evaluation and assessment criteria. This includes performance, cost effectiveness, timing, risks, reliability, environment, and other pertinent factors. These criteria will define the goals of each optimization process.
7. Perform parametric analysis and optimization trade-offs at the system level including the following considerations (subsystem level trade-offs must be done as part of the subsystem effort):
 - (1) Transportation Systems - This will include the establishment of mission profile options, and the derivation of mission profile induced subsystem requirements like propulsion system performance and payload accommodations. Definition of recurring costs per pound of payload, orbital decay effects on assembly operations, and the influence of plasma and radiation belt environment will yield critical trade-off parameters for transportation

system optimization. Parameters developed under "Transportation System" must be considered here. The parametric analysis and optimization trade-off must cover all transportation requirements:

- (a) Earth to Low Earth Orbit
- (b) Low Earth Orbit to Geosynchronous Orbit
- (c) Assembly Transportation in both orbits required for partial low Earth orbit and final geosynchronous orbit assembly.
- (d) Logistic Transportation for delivery of spares and expendables to both orbits.
- (e) Maintenance Transportation for operational SPS maintenance and service.
- (f) Crew Transportation to both orbits in support of assembly and operational requirements.

(2A) Orbital Power Station Systems

- (a) Primary system considerations here are to perform configuration trade-offs and optimizations of system size and weight as function of power on the ground; the delivery, assembly and deployment modes and the structural options for both the collectors and the microwave antenna. Closely associated with the structural options are the power distribution options within the SPS whether they are independent or structurally integrated. Other system optimizations have to cover mechanical assemblies like rotary joints, and others.
- (b) Define critical parameters that involve the orbital mechanics affecting the operational SPS: Stabilization and control modes, the external effects of radiation pressure and gravity influences and satellites internal effects of electromagnetic torques and interactions. Define propellant requirements, eclipse cycles and their duration and microwave link performance as function of travel distance through the atmosphere. These are related to orbital position and will yield important trade-off parameters.

- (c) Perform analysis of flight control and structure dynamic interactions, of radiation and micrometeoroid hazards, and of structural thermal equilibrium conditions that will provide optimization parameters.
- (d) Define cost envelopes and boundaries that will indicate primary and subsequent cost drivers required for cost and economic optimization.

(2B) Orbital Power Station Subsystems

After the Orbital Power Station System parametric sensitivity analyses and optimizations have been accomplished, the same approach shall be followed to perform detailed investigations in the subsystem areas, using the subsystem requirements and overall optimum parameter ranges established by the system optimization for each system option.

- (a) The solar collector and conversion subsystems trade-offs and optimizations have to include an analysis of the required performance and optimization with the associated cost data. Energy conversion options like thermal concentrator/collectors and photovoltaic converters have to be compared based on design and manufacturing concepts, on operating life and maintainability, to name just a few parameters.
- (b) The microwave generation and transmission subsystem trade-offs and optimizations have to include performance analyses and thermal design parameters for both the transmission antenna and the direct current microwave converter. In addition perform analysis, parameter definition and optimization of the phase front development and maintenance elements, the power distribution configuration and the pointing and control approaches. Important aspects of the direct current-microwave converter are performance/cost optimizations and service life and maintainability parameters.
- (c) Other subsystems like the electrical and control subsystems must follow similar analytic and optimization sequences.

(3) Ground Systems

Establish trade-off parameters and perform optimizations including the following key elements and their options of the ground systems and their subsystems:

Analyze the receiving antenna and associated power density control elements down to their key parameters for maintenance and service, the effects of malfunction of major elements, environmental control, and overall safety. The distribution of power as well as the total utility interface are parameters that may reflect significantly upon the orbital systems configuration, and their optimization has to take into account related orbital system parameters.

System analysis has to cover parameters like minimum safe pool sizes, various transmission systems interconnecting SPS to terrestrial power network, energy storage desirability and options for either load averaging or safety. The degree of possible optimization of ground systems will affect the technical and economic feasibility of SPS.

Define any required technical developments in storage, transmission, network expansion and design and system control.

Perform trade-offs on site location with regard to distance from load, environment, and climate characteristics.

(4) Assembly and Maintenance Operations

These systems and their various subsystems which cover ground, low Earth orbit and geosynchronous orbit operations can be implemented in a number of ways. Define options and their significant parameters and subsequently perform trade-offs and optimizations including the following areas:

- (a) Ground packaging and transportation of SPS modules of payload size.

This element has a major impact on the SPS structural design.

- (b) Ground assembly, system and subsystem test and verifications, disassembly and vehicle loading. These elements require careful definition of all possible options and their subsequent trade-offs and optimizations.

- (c) Low Earth orbit assembly, associated equipment and resources.

Define suitable options and parameters and perform the necessary trade-offs and optimizations.

- (d) Low Earth orbit to geosynchronous orbit vehicle integration. In conjunction with the vehicle definition parameters define and optimize the combined vehicle-structural assembly entity for stability, control, performance and cost effectiveness and other pertinent parameters.
- (e) Geosynchronous orbit assembly and checkout. Define suitable options and parameters, perform the necessary trade-offs and optimizations.
- (f) Assembly operations support crew. Define various options of mixes between manned and automated operations. Perform parameter definitions concurrent with SPS structural definition.
- (g) Maintenance considerations over the projected lifetime of the Power Station.

8. Systems Integration

- (1) Utilizing the results of the foregoing system analyses perform a total system integration by using the optimized system elements and define the critical interfaces generated by the integration.
- (2) Size the total system covering transportation, orbital system, ground and operational systems and subsystems.
- (3) Determine the total system efficiency, performance, cost, masses, reliability, and maintenance.
- (4) Update the baseline systems using the results of the integration effort and perform a comparison with the original system requirements.
- (5) Perform necessary iterations of the preceding system analysis and engineering effort to:
 - (a) Incorporate advanced technology.
 - (b) Eliminate discrepancies between system requirements and integrated system characteristics.

9. Economic Analysis and Costing (See also "Economic Commonality")

In order to assure that equitable decisions are made between various satellite power systems options, cost and economic data must be supplied on the technically feasible systems for given energy production levels. Care must, therefore,

be taken that the analyses be performed on comparable systems. A cost and economic analysis must consider that life-cycle costs be generated in constant, current-year dollars reflecting the expected cost to be incurred in each year of the project life and include the total development, investment and operations costs attributable to each system over the life of the project.

An analysis should be performed to determine the optimization point between development expenditures and operating costs.

The above work should ensure an equitable comparison of all systems with regard to direct dollar costs and benefits.

Recommended Approach

In order to meet the objectives of this critical area, on-going and planned technology development efforts have to be supported by a continuous overall critical system analysis and integration effort which absorbs any available or newly developed technology data and information into its trade-off and optimization processes and in turn provides new guidelines, options and emphasis to the technology efforts.

A second important effort is needed to define an evolutionary sequence of technology demonstrations on the ground and in space. These intermediate milestones must provide valid verification of the results of technology developments toward an SPS. An important aspect of these technology demonstrations is the desirability for multiple applications of the demonstration projects in case the SPS is not implemented. These alternate applications need to be considered concurrent with the demonstration requirements.

Based on the foregoing rationale the following studies are required:

1. Critical SPS System Analysis and Optimization

This continuous study effort will systematically proceed through the following steps in a number of iterations as required by the program:

- (a) Definition of the various system and subsystem requirements as dictated by the demands imposed on them and by the needs these elements have to respond to in the overall system function and operation.

- (b) A sufficient description of suitable system and subsystem options that respond to the established requirements.
- (c) A set of evaluation and assessment criteria to be used in the comparison of options.
- (d) A trade-off process between system and subsystem options to single out the most potential candidates for further optimization.
- (e) Optimization of candidate systems and subsystems.
- (f) Integration of optimized subsystems into selected system candidates.
- (g) Resources impact analysis for one to one hundred SPS's.
- (h) Derivation and compilation of critical SPS technology development requirements. This includes the definition of physical, financial, and scheduling constraints, of the technology categories involved, a description of the necessary technology development tasks, schedules, milestones, and resources.

2. Intermediate SPS Program Milestone Definition

In order to provide the necessary decision opportunities during the SPS assessment program, certain intermediate milestones need to be defined.

This task will consist of:

- (a) Analyze and define scaling constraints. The various scaling factors involved in demonstrating the very large and heavy power satellite elements separately and integrated will result quite often in mutually exclusive characteristics of the demonstrated object. These scaling constraints must be analyzed and demonstration optimization analyses and plans must be developed.
- (b) Define specific technology verification and demonstration activities. These activities may involve:
 - Early pilot demonstrations.
 - Intermediate subsystem demonstration.
 The configurations and scope of these demonstrations must be optimized with regard to the intended verification.

- (c) Consider alternate uses of demonstration hardware and results for the case where the program goals cannot be achieved. These optional applications form an important part of this investigation.
- (d) Define a comprehensive ground and space test program where the utilization of the Space Shuttle will form the basis for space borne critical components, subsized assemblies and subsystem testing and verification plans.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Capabilities and Experience

1. System Analysis and Integration of Large Systems

From its very beginning, NASA has had its attention concentrated on the total system approach and has developed unique methods and techniques in the establishment and control of requirements, trade-offs, optimization, costing, and in the execution of system and subsystem analysis and integration. These capabilities have been successfully applied to highly complex programs like the Saturn/Apollo, the Skylab and others, and are presently being applied to the Space Shuttle, High Energy Observatory, Planetary Spacecraft and many others.

2. System Management of Large Systems

NASA has developed a unique methodology of managing very large systems. The fundamental key is Baseline Control where broad baseline objectives are established by contract specifications, requirements, standards, and documents. As a program progresses, these baselines are made more definitive through program management reviews and design reviews. Maximum efficiency, program visibility and control are achieved by configuration management, change control and accounting.

3. Costing

Centralized offices for costing efforts, including costing requirements, are available. These include formats, methodology, techniques, data bank, independent cost estimates, review and validation of contractor estimates,

SYSTEM ANALYSIS AND ENGINEERING (A.3)

Preliminary Program Estimates

Cost and Schedule

TASKS	FY	1	2	3	4	5	
(1) Critical SPS System analysis and Optimization. 2 Parallel Contracts \$1.5M each for 5 years.		←		\$15M		→	
(2) Intermediate SPS Program Milestone Definition 2 Parallel Contracts \$0.75M each for 4 years			←	\$6M		→	

"grass roots" type cost estimates, mechanisms for review of cost plans, comparisons with actual cost, coordination and involvement with NASA comptroller reviews.

② Applicable Efforts

1. Studies

- ④ "Space Based Solar Power Conversion and Delivery Systems Study" now in progress.
- ④ "Space Based Power Conversion and Power Relay Systems" study to begin in July 1975.
- ④ Payload Utilization of SEPS (PLUS)

2. R&D In-House With Contractor Support

- ④ Solar Concentrators/High Temperature Collectors
- ④ Design Optimization
- ④ Fabrication and Costing
- ④ Test and Evaluation
- ④ Large Scale, High Power Solar Array Technology Development

A.4 UTILITY INTERFACE

Criticality

The utility interface area is critical to the design definition and optimization of the SPS because it will establish the output requirements and characteristics of the overall system. The output parameters determined will be the fundamental bases on which the technical and economic feasibility of the SPS will be ultimately assessed.

Utility interface requirements must satisfy utility service needs, however, unnecessary or unduly stringent requirements must be avoided. This can be accomplished only by thoroughly investigating the range of functional characteristics, operational requirements, projected power and energy capacities and demands and other factors that significantly influence the SPS design.

The utility interface area deals with the ground system that converts, conditions, and controls the energy received from the orbital system, and subsequently, delivers the necessary power to the interface in a form and manner that must be compatible with the existing utility system. Being the last link in the SPS chain, the ground system performance and operational requirements significantly affect the overall system performance and potentially impose critical requirements on the space systems. Therefore the ground system must be designed and optimized with respect to both the space systems and the utility interface.

The type of equipment for some of the major elements, and the size of the ground system are unprecedented for a single generation site. Investigations are highly important to determine whether or not undefined technology constraints exist within the system as well as to determine the design and performance characteristics required of expected critical elements. Except for the primary converters (expected to be DC-AC) the components of the ground system are not expected to be technology critical. Nevertheless the ground system/utility interface represents a significant part of the SPS and the determination

of parameters affecting resources, investments, and operational costs are considered critical to the optimization and feasibility of the system. In addition, the problem of power outage during the infrequent predictable occultations of the orbital power station must be addressed and any requirements on the SPS identified.

Another aspect of the utility interface area considered critical to the justification and implementation of the SPS, is the establishment of technical coordination and data exchange activities with the utility industry to assure the validity of requirements and projections, and to encourage their participation and fiscal support of the program.

Objectives of Required Efforts

Valid, realistic design criteria and parametric data related to performance and economics must be established as soon as practical to support the studies and technology efforts planned for the various critical areas and to expedite the system engineering and analysis efforts required. The overall intent of the objectives set forth is to create a sound basis for the various feasibility assessments to be made of the SPS.

1. To establish functional characteristics, design and performance criteria and operational requirements imposed by the utility interface that must be satisfied by the overall SPS.
2. To develop parametric performance data and design related economic factors (e.g. installation, operating, and maintenance costs, revenue rates, etc.) consistent with the experience and projection of the utility industry that significantly affect SPS planning and optimization studies and that will serve, ultimately, as a basis for usefulness and economic appraisal of the SPS program.
3. To define an SPS ground power system that will assure that functional and operational characteristics are compatible with candidate utility interfaces and that will, within technology and economic constraints, optimize the overall SPS system to sustain maximum power and energy at the interface for minimum cost to the aggregate system.

4. To determine what technical developments in the utility sector are required (e.g. transmission, network expansion, system control, primary DC-AC inverters storage), to develop preliminary requirements for such items, and to assure technology effort are initiated as soon as practical, consistent with program priorities and resources.
5. To establish contacts and coordination activities with the utilities industry to exchange design, operational, management, and future planning information and to encourage technical participation in SPS planning activities.

Recommended Approach

General Concepts

An approach, consistent with that proposed for "System Analysis and Engineering", is recommended for efforts in the utility interface area. The SPS ground system and the utility system should be studied as a composite system in order to optimize the output and usefulness of the aggregate system from a user's standpoint. Initial emphasis should be placed on the early establishment of reasonable interface requirements, design guidelines, and parametric data needed for efforts planned in various critical areas and for overall system optimization. Such efforts will enhance the credibility of subsequent system studies and assure significant requirements, that may emanate from the utility interface, are not overlooked in other critical areas.

Close coordination with system engineering activities will be required to support mainstream design and analysis efforts and studies dealing with influences between systems and major elements of the SPS. To provide realistic requirements and data, and to insure the quality of study results, an iterative process must be followed whereby information and concepts are periodically updated as studies progress.

Involvement of the utility industry is required not only to obtain technical design and operational criteria but to take advantage of their experience and methods in projecting such things as loads, system expansion, economic factors,

and future resources required.

The extent of technology efforts required in the utility interface sector is yet to be defined and is one of the purposes of the studies recommended. It is anticipated that technology work will be required for the primary power converters that will receive and condition SPS power for delivery to the utility interface. Such efforts will be recommended as soon as studies indicate the optimum type and specific characteristics needed.

Design and Analysis Studies

1. Utility Service Requirements. Investigate appropriate geographical and utility service areas and establish information and statistics pertinent to selecting an optimum receiving site and a utility system for the initial SPS application. Identify, for example, present and projected load centers, power and energy demands, utility facilities and capabilities, and energy resources used, required, and available. Select a number of candidate areas and acquire statistics on power outages, weather conditions, population/industrial distribution and terrain.
2. Utility System and Interface Analysis. Perform systems and operational analyses on a representative cross section of utility system candidates to determine typical ranges of system loads, demands, and functional characteristics. Determine the power generation, energy, and transmission capabilities available, and the capacity displacement committed for service. Define requirements and practices for supervision, operational control, communications, protection, redundancy and maintenance. Investigate the range of functional characteristics, operational supervision and control, safety, and reliability requirements imposed on a utility system. Determine the performance experienced with the various subsystems, types of equipment and installations. Also define design, operational, and economic criteria and methods used to project system expansion, resource requirements, costs, and service rates.

3. Interface Optimization and Requirements. Perform and system performance and operational analyses of one or more SPS integrated with candidate utility systems to evaluate SPS interface requirements and the capability of the composite system to meet the utility service requirements projected for the given area. Investigate possible dynamic interaction between the utility and the SPS associated with power routing and absorbing peak demands. Evaluate system transient and response characteristics for emergency load and fault conditions, and for lightning strikes. Determine potential effects on major elements of the SPS. Define system and subsystem concepts and their design and performance requirement to satisfy interface and aggregate system demand requirements and to optimize the performance reliability and stability of the overall system.

Incorporate updated information, alternate concepts and configurations, including utility system capability and technology projections, and iterate studies to evaluate approaches that optimize the output of the composite system. Assess and compare utility margin requirements for design, performance, and capacity. Evaluate effects and requirements of (1) power and energy demands and control, (2) projected utility capabilities to receive and handle various forms and levels of power, (3) outages (including SPS occultation periods), (4) reliability, and (5) capacity displacement. Perform technical and economic tradeoff analysis of promising candidates and select a baseline and alternate approach for subsequent studies. Predict the "capacity displacement" and optimum, realistic design and performance requirements for the SPS - utility interface.

4. Subsystem Definition. Establish guidelines and requirements by the utility interface on the various subsystems and major elements of the SPS ground system. Establish concepts and tradeoff criteria and evaluate to select several promising candidates for further investigation and for system optimization studies.

Technology Efforts

In general technology effort requirements in the utility interface area have not been defined. However, the primary power converter is a technology item critical to the performance and feasibility of the SPS that is likely to require development efforts. Although an optimum type and specific characteristics have not been defined converters capable of handling unprecedented levels of power at very high efficiency will be essential. Concerted efforts should be made to establish criteria and to initiate technology development of this item as soon as practical. Scale model test and performance demonstrations are also recommended because such converters are considered critical to the feasibility of the SPS.

Preliminary Program Estimates

● Costs and Schedules

The costs for ground system and utility interface studies are dependent on the input information expected of other areas, the coverage of the subject in mainstream SPS studies, and on the type of utility company participation. Since initial efforts are somewhat exploratory, costs may also be dependent on requirements or problem areas determined in the earlier studies.

Study costs are based on a projected five year effort. Technology efforts extend beyond this to approximately eight years. Cost and schedule information are given in the following chart.

● Available Technology

Technology requirements have already been indicated for primary power converters and may exist in other areas such as energy storage. Most of the applicable technology available rests with the utility industry and will be investigated during studies. However, it is anticipated that it will be adequate to overcome problems and to satisfy requirements. Ground system design and equipment will be determined primarily by performance and cost. Not being subject to weight, launch costs, and other space system constraints, technology requirements

UTILITY INTERFACE (A. 4)
Preliminary Program Estimates
 Cost and Schedule

TASK	FY	1	2	3	4	5	6	7	8
SERVICE AREA REQUIREMENTS (2 CONTRACTS, 40K TOTAL)		25K				15K			
UTILITY - NASA COORDINATION (DOCUMENTS/TRAVEL at \$10K/YR)			50K						
UTILITY SYSTEM - INTERFACE ANALYSIS - DATA (2 CONTRACTS, 1 YR. at \$75K Each)		75K	75K						
UTILITY - SPS OPERATIONAL/ PERFORMANCE OPTIMIZATION AND INTERFACE REQUIREMENTS (1 CONTRACT, \$100K/YR)			200K						
GROUND SUBSYSTEM DEFINITION AND SPS OPTIMIZATION ANALYSIS (1 CONTRACT, \$100K/YR.)				300K					
CONVERTER TECHNOLOGY - DESIGN FABRICATE (1 CONTRACT, \$600K/YR.)					1800K				
CONVERTER DEMONSTRATION DOCUMENTATION (1 CONTRACT \$200K TOTAL)								200K	

for ground items will be much less severe. NASA developed technology in instrumentation, communications, fault protection, system control, etc. is applicable and sufficient.

● Experience and Capabilities

NASA has considerable experience in the design implementation and management of large scale systems and studies. All engineering and technical disciplines required for SPS ground system efforts exist within NASA. Personnel training and experience is formidable and they are highly qualified to accomplish challenging tasks. Numerous computer facilities exist that are not only adequate but are expected to expedite the subject work. Also many of the programs and mathematical models available are expected to be highly beneficial to SPS activities.

Untold utility system experience exists in the industry and will be needed in this area. Contacts and coordination activities will be established to apply this experience to the SPS. In addition, large scale test facilities, complexes, launch facilities, and ground systems, involving utility and other support services, have been designed, built, and operated by NASA personnel for Saturn-Apollo and numerous other vehicles.

● Related Programs

The utility industry has supported research and technology programs on very high voltage equipment, on DC transmission lines, to improve efficiency and cost of energy conversion, and on energy storage that are considered applicable. NASA has conducted numerous studies, R&D projects, and systems programs related to the generation, conversion, distribution, and control of electrical power and energy. For example, "Lunar Energy Depot" and "Space Station" studies dealt with new and large power systems, but these systems would be tiny compared to SPS. Two newly established space based power conversion system studies may produce useful data, however, these are not expected to treat ground systems and utility subject to any degree. Power R&D

projects referenced for other critical areas are also applicable. The solar utilization and solar heating and cooling projects underway, may also provide significant useful data for the SPS.

B. SPACE SYSTEMS

B1. HEAVY LIFT LAUNCH VEHICLE (HLLV)

Background

The elements of the space power satellite will be manufactured on Earth. These elements must be packaged into payload modules and transported from a launch site on Earth to an assembly station or staging point in low-Earth orbit by a launch vehicle of sufficient size to carry the largest irreducible element of the SPS system. Since one operational power station on station in geosynchronous orbit has an estimated mass between 10 and 50 million Kg, and propellant supply for the vehicle which transfers the station elements from low-Earth orbit (LEO) to geosynchronous orbit (GSO) will be in the range of 30% to 300% of the net on-station mass, launch operations of unprecedented scale and frequency may be anticipated. Since the launch operation is expected to constitute from 10% to 30% of the acquisition cost of electrical power from space, the operations costs associated with this HLLV are of critical importance.

Criticality

If a cost of \$44/Kg (\$20/lb.) to low-Earth orbit can be achieved, the HLLV transportation costs will represent an estimated 10 to 30% of a potentially acceptable unit electricity cost. This cost includes the acquisition, maintenance and operations of the HLLV fleet. Current opinion is that \$44/Kg is an ambitious but possible target for a 300 to 450 metric ton (661-992K lb.) class HLLV with a high annual launch rate. The extrapolation of the existing Shuttle and Apollo-era study data base to this scale requires significant review and new systems synthesis efforts to gain confidence in these opinions relative to launch costs.

Objectives of Required Efforts

1. Define the requirements to be met by a HLLV designed to deploy the elements of an operational space power satellite system (SPS).

- Mass of payload per launch
 - Volume of payload per launch
 - Launch rate, launches/yr vs. year of operation
 - Targeting accuracy and rendezvous maneuvers required
 - Services required to be supplied to the payload (environmental protection through launch, electrical power, downlink data, thermal control, etc.)
 - Maximum "g" loading tolerable to the payload
 - Required operational capability date
 - Utility of external propellant tankage as structural elements or raw materials for orbital construction of the SPS (a "negative" requirement, greatly relieving upon reusable vehicle design requirements)
 - Personnel and equipment launch and return requirements
2. Define prime and backup HLLV candidate configurations to meet the requirements, differing by the technology levels utilized and acceptance of program risk.
 - Size and weight
 - Configuration
 - Launch and recovery vehicle features, ground facilities and equipment
 - Operations cost
 - Fleet size
 - Development and fleet acquisition costs
 3. Define flight and ground operations - techniques, software and facility requirements, staffing and management concepts.
 4. Define environmental effects, terrestrial energy consumption, and scarce materials consumption of projected launch activities for each candidate HLLV concept.
 5. Develop implementation plan for the candidate HLLV's - schedule and resource needs.
 6. Develop technology plan to support development of HLLV.
 7. Develop performance/cost sensitivities and program risk data around nominal values.

Recommended Approach

1. Studies

- The "Future Space Transportation Systems Analysis" study, now in progress at Boeing for JSC is addressing the HLLV requirements of the SPS program as one of twelve possible future space activities. Special added emphasis can be placed upon the specific SPS program requirements area.
- MSFC currently has two economic/system engineering studies of the photovoltaic and solar-thermal versions of the SPS underway, "Space-based Solar Power Conversion and Delivery Systems." A task of these studies requires forecasting HLLV requirements, characteristics and cost. These data are expected to contribute to a better understanding of launch vehicle requirements, including cost goals, for a successful SPS program.
- The "Systems Concepts for STS Derived Heavy Lift Launch Vehicles" study for JSC is expected to begin in July 1975. This is a \$300K, 12-month study which will define optimized vehicles for various payload classes and usage rates, including anticipated space power satellite requirements. When this study is completed, a conceptual design for a family of HLLV's to meet a broad range of mission scenarios and better \$/Kg to low-Earth orbit estimates will be available. A further study utilizing this background plus better SPS requirement definitions, will be useful at the midpoint or later in this study.
- LaRC presently has two study contracts in progress for technology requirements of advanced launch vehicles (single-stage-to-orbit) of the 65,000 lb. payload class. These studies could be augmented or redirected to examine technology requirements of the larger vehicles indicated for SPS deployment.
- LeRC currently has a study contract on an advanced technology O_2 /hydrocarbon engine for launch vehicle boost application. This study could be

accelerated and augmented to better serve the SPT need dates.

2. Experiments - none
3. Hardware development - as structures, materials and propulsion concepts for HLLV's evolve, limited advanced development hardware fabrication and test will become necessary to reduce cost and technical uncertainties, current activities of this sort within NASA which are deemed supportive to the HLLV might be supported to perform at an accelerated pace and/or to consider new alternatives.
4. Supporting activities - LaRC and JSC have active programs of "computer-aided design" which is under development to enhance the NASA capability to do space system synthesis. This capability, as it now stands, has already demonstrated the ability to rapidly produce useful data on new launch vehicle concepts. Since the current programs are primarily intended to develop this new design capability, the resources now available to accomplish launch vehicle simulation and sizing are sharply limited. Similar activities are underway at JSC and elsewhere to improve, through use of the digital computer, the cost estimation capability of the NASA. Similar limitations of resources for actual simulation use might be corrected to increase the confidence in contractor-generated cost estimates or provided alternative estimates of cost.

Preliminary Program Estimates

- Cost and Schedule (see chart)

HEAVY LIFT LAUNCH VEHICLE (B.1)

Preliminary Program Estimates

Cost and Schedule

	<u>FY76 & TP</u>	<u>77</u>	<u>78</u>	<u>79</u>
- Augment MSFC study tasks re HLLV in current SPS economic studies	2 @ 50K ea = 100K	-	-	-
- Add SPS special emphasis task to Phase II of JSC FSTSA study	75K	-	-	-
- Add SPS special emphasis to JSC HLLV sys. study	75K	-	-	-
- Add HLLV tasks to LaRC SSTO studies	2 @ 75K ea = 150K	-	-	-
- Increase scope and manning level of LaRC O ₂ /hydrocarbon engine study	50K	150K	250K	500K
- Phase A studies of STS HLLV	-	2 @ 250K = 500K	500K	-
- KSC study of ground operations of HLLV's	75K	150K	300K	-
- Mission control and flight software requirements of HLLV's	75K	150K	300K	-
- Computer-aid design HLLV simulation - JSC	60K	90K	90K	-
- Computer-aid design HLLV simulation - LaRC	60K	90K	90K	-
- Independent cost analysis of HLLV concepts	-	50K	100K	100K
- Energy analysis of HLLV	80K	120K	170K	200K
- HLLV technology plan formulation	-	100K	100K	-
- SPS HLLV φ B studies (2)	-	-	-	4M
TOTALS	800K	1.4M	1.6M	4.8M

⊕ Capabilities and Experience

- MSFC, LeRC and JPL have extensive experience in the development of booster systems. JSC is now acting as lead Center in the development of the Space Shuttle system, with key roles delegated to MSFC, KSC, LaRC, and Ames and other Centers.
- JSC has extensive experience in operating world wide systems for the launching, tracking and recovery of spacecraft and in developing the necessary software and operations management systems.
- The aerospace industry has a great breadth and depth of experience and talent now available to be applied to the HLLV for the SPS as a direct consequence of the intensive corporate efforts during the recent space shuttle Phase A, B, and proposal preparation studies. This skilled manpower pool, coupled with the data base available from the 17 years of U.S. space flight experience from Explorer I to ASTP, represents a fully capable national resource to conduct a successful HLLV project for the SPS program. Current studies are underway under company sponsorship for advanced launch systems - an expression of interest and intent on the part of the NASA toward the HLLV can be confidently predicted to mobilize this resource in an innovative and energetic fashion to meet the goals of the SPS HLLV project.

B.2. TRANSFER VEHICLE

Background

The space power satellite will be assembled, in part or in its entirety, in low-Earth orbit from equipment and materials delivered from Earth. Once assembled in LEO, the satellite or modules of the satellite must be transported to the geosynchronous operating orbit. The cost of the element of the SPS system to achieve this transfer is expected to be a significant contribution to the investment in the operating satellite. These costs consist of the DDT&E, acquisition, maintenance and operations of the transfer vehicles, the delivery of the vehicles, their propellants and logistics needs to low-Earth orbit, production of the propellants, the costs associated with design of the satellite or modules to withstand the LEO-GSO flight environment produced by the transfer vehicles, and the interest costs on the capital invested in the payload during its lengthy transit to geosynchronous orbit.

Preliminary indications are that high Isp, low thrust propulsion systems are necessary to reduce the mass of propellant to be delivered to LEO. The high-thrust chemical rocket will, however, be the standard by which the relative merits of the competing, more advanced propulsion systems will be measured.

A first-order determinant of the advanced propulsion system transfer vehicles weight and cost is the availability of electrical power from the power satellite module being transported, as payload of the vehicle, to GSO. Should a separate, dedicated power supply be necessary, the costs of this transportation segment will be increased.

Since the time required to transfer the payload from LEO to GSO by the advanced, low thrust transfer vehicle is measured in tens or hundreds of days, systems analysis may identify a requirement for a much smaller chemical propulsion vehicle than the "standard" transfer vehicle which is capable of transporting personnel and less massive high-priority cargo from LEO to GSO or return with a 5 1/2-hour trip time. Such a vehicle may find additional use, for the transfer vehicle which derives power from the outbound payload module, in

returning the transfer vehicle to low orbit for replenishment and reuse.

Since the satellite power station modules are expected to encompass very large areas (square kilometers) their mass will be distributed such that thrust loads may not be tolerated at a single attachment point. The structural loading limitations imposed by the SPS payload module during the transfer, the necessity of providing attitude control and orbit stationkeeping during construction in LEO, and of accommodating center of gravity/center of pressure offsets during the transfer, all indicate an unorthodox propulsion vehicle design which may be distributed as propulsion modules on the payload structure. Autopilot and attitude control system requirements of the transfer vehicle may therefore assume a new dimension.

Criticality

Although ion propulsion units have been flight tested in SERT 1 and SERT 2, and in-depth studies have been accomplished on the solar-electric propulsion stage (SEPS), little direct data exists on high performance propulsion systems of the scale required for the SPS. Consequently, estimates of the transfer system weight, performance and cost are now highly speculative. Since this transfer operation drives the mass required in low-Earth orbit, and can itself require a large investment in the vehicle fleet, it is expected to be a major contributor to the electrical energy cost of the SPS. The current uncertainty in the key parameters of the transfer vehicle must be reduced in the Satellite Power Team assessment interval to support valid SPS system cost estimates.

Objectives of Required Efforts

1. Define the requirements to be met by a chemical propulsion transfer vehicle designed to deploy the modules of an operational space power satellite program from the LEO assembly point to GSO.
2. Define the requirements to be met by a low thrust, high specific impulse transfer vehicle designed to deploy the modules of operational space power satellites from LEO to GSO.
3. Determine if the payload modules can be utilized to provide the electrical power supply to the electric propulsion transfer vehicle.

4. Define the requirements (if any) for a manned, high priority cargo chemical propulsion transfer vehicle to support an operational SPS program.
5. Perform transfer vehicle/satellite structural design trade studies.
 - Payload module weight/configuration vs. payload design and operations penalties
 - Transfer maneuver accelerations and load distribution vs. payload design penalties
 - Program cost and payload degradation penalties vs. transit time
 - Payload weight and degradation penalties vs. power/cooling/etc. supplied from payload to transfer vehicle
6. Generate preliminary definition of several candidate transfer vehicle concepts.
 - Chemical propulsion cargo vehicle
 - Independent ion propulsion stage
 - Dependent ion propulsion stage
 - Dependent MPD propulsion stage
 - Dependent arc jet thruster stage
 - High thrust/mass ratio personnel and high-priority cargo vehicle
7. In coordination with the satellite power system designs, define the mass and mass distribution, flexibility geometry, attitude control, and other factors affecting the transfer vehicle.
8. Evaluate potential thrusters for chemical rocket engines, MPD thrusters, ion thrusters, and direct-heated working fluid engines.
9. Characterize and evaluate candidate propellant fluids, including estimation of availability in the quantities determined necessary, cost of acquisition, storability, space transfer from the LEO delivery container to the stage, safety, environmental compatibility, materials compatibility and behavior within the thruster system.
10. Obtain engineering thruster data at high impulse with various propellants sufficient to define thruster scale up factors, power processor and/or

high voltage array requirements or options, and baseline propulsion system interfaces.

11. Perform parametric definition of power conditioning subsystems.
12. Develop design concepts and performance requirements for payload independent power supplies.
13. Establish methods of reducing the impact of near Earth radiation environment plasmas on transportation system power sources.
14. Perform thermal assessment of vehicle concepts.
15. Perform preliminary design of selected prime and backup transfer vehicles. Identify associated costs, lifetime, mass, and other operational factors.
16. Determine impact of transfer vehicle on the satellite attitude control system.
17. Perform preliminary design of a high-thrust chemical propulsion stage for fast transfer of personnel and high priority freight.
18. Define flight and ground operations - techniques, software and facility requirements, staffing and management concepts, including studies of LEO and ground refurbishment/replenishment of the candidate vehicles.
19. Develop implementation plan for the candidate transfer vehicles schedule and resource requirements
20. Develop technology and component development plan to support timely development of the candidate transfer vehicles
21. Develop performance/cost sensitivities and program risk analysis around nominal values.

Recommended Approach

1. Studies

- Augment the MSFC "Space-Based Solar Power Conversion and Delivery Systems" studies to develop preliminary transfer vehicle requirements document.
- Augment the JSC "Future Space Transportation Systems Analysis" study to develop transfer vehicle requirements for SPS delivery and provide additional parametric data on candidate concepts for transfer vehicles,

including chemical and electric propulsion concepts.

- Evaluate in-house at MSFC the existing Tug/IUS and SEPS data applicability to the SPS requirements
- Expand MSFC "Payload Utilization of SEPS" study to conceptually define the independent, photovoltaic ion propulsion transfer vehicle option

2. Experiments and other hardware efforts

- Continue and expand thruster and power conditioner development and life-time demonstration work at LeRC, including design, build, and test bombardment thrusters with several candidate propellants. Define thruster performance, lifetime, fields and particle interface characteristics, reliability, and projected cost as a function of propellant type, input power, specific impulse, and thrust level.
- Reinitiate breadboard arc jet thruster demonstration/technology development.
- Design, build, and test a small scale solar reflector-high intensity solar array system. Determine reflector optical-thermal requirements, solar array performance and thermal control requirements, and preliminary estimates of system mass including provisions for radiation and plasma protection.
- Continue large scale, high power solar array development at MSFC.
- Propellant/materials properties tests associated with electric propulsion systems.
- Expand LaRC and LeRC fluid transfer shuttle experiment definition.
- Define and conduct expendable LV space experiments/flight demonstrations of selected electric propulsion system components.

Preliminary Program Estimates

Cost and Schedule - An in-house NASA effort at MSFC, JSC, LaRC, and Ames is anticipated. In addition, a suggested program requiring R&D funding for the definition of transfer vehicles meeting operational SPS program requirements is shown on the following chart.

TRANSFER VEHICLE (B. 2)
Preliminary Program Estimates - Cost and Schedule

	<u>FY76 & 1P</u>	<u>FY77</u>	<u>FY78</u>	<u>FY79</u>
Add special emphasis tasks to MSFC "Space Based Solar Power" studies for transfer vehicle requirements definition	2 @ 50K = 100K	-	-	-
Add SPS special emphasis task to Phase II of JSC FSTSA study	75K	-	-	-
Add-on to MSFC SEPS PL study - conceptual definition of independent, photovoltaic transfer vehicle	75K	-	-	-
JPL in-house systems evaluation of transfer vehicles technology readiness and concepts	300K	300K	300K	300K
New Ames study - concept and operations definition of arc jet/MPD transfer vehicles	150K	150K	50K	-
High impulse thrusters (ion, arc jet, MPD) development test programs	300K	700K	1.2M	1.5M
Radiation-resistant power source development test program	200K	500K	800K	1.0M
Propellant properties characterization	50K	100K	100K	100K
Propellant storage and distribution development test	-	50K	100K	150K
Direct solar-heated thermal rocket concept development test	75K	150K	300K	-
Flight demonstration test definition studies	-	150K	300K	-
Mission operations and software analysis	-	50K	150K	300K
Power supply and conditioning development tests	-	100K	300K	500K
Transfer vehicle system requirements studies (2)	-	200K	-	-
Chemical transfer vehicle conceptual design	-	100K	300K	-
Independent transfer vehicle conceptual design	-	50K	150K	300K
Dependent transfer vehicle conceptual design	-	-	100K	400K
Manned transfer vehicle	300K*	300K	500K	750K
Energy analysis of transfer vehicles	75K	150K	250K	100K
Transfer vehicle heat rejection requirements and technology definition	-	50K	100K	100K
TOTALS	1.7M	3.1M	5.0M	6.0M

*In NSF UPN 981 FY76 draft pad as JSC study

● Technology Assessment

- Experience with thruster operation up to 25,000 seconds with many propellants exists at LeRC.
- High intensity solar array technology exists within the federal government and private industry.
- Propellant system would require technology from ongoing materials research efforts but little other high technology.
- GSFC has experience in low thrust system applications.
- Ames and JSC have significant arc jet test facility activities pertinent to propulsion applications.
- JPL has long standing experience in advanced chemical propulsion technology and space systems development for unmanned planetary applications.
- MSFC has long standing experience in electrical vehicle system/subsystem design, development, technology, and operations in Earth orbit and planetary applications.
- MSFC, JSC, LeRC have managed the development and applications of chemical stages of the type required as a transfer vehicle and have in-house capability for study and program management of transfer vehicle activities.

● Applicable Efforts

- NASA program for development of electron-bombardment thrusters and other critical thrust system elements.
- NASA sponsored systems studies of electric propulsion near Earth transportation systems.
- Boeing is now engaged in a broad future space transportation systems analysis study for JSC which includes treatment of transfer vehicle for the space power satellite.
- Other aerospace firms have in process related technology and systems studies for NASA and DOD.

- Electric Transfer Vehicle - Boeing, Rockwell International, Hughes, TRW, and others have suitable experience to qualify for work in this area.
 - Related Contractor Studies
 - Recently completed SEPS Definition Studies at MSFC (Boeing and Rockwell International)
 - SEPS Applications Study at MSFC (recently awarded to Boeing)
- Chemical Transfer Vehicle - Boeing, Rockwell International, McDonnell Douglas Astronautics, General Dynamics, Martin and others have suitable experience to qualify for work in this area.
 - Related Contractor Studies
 - Boeing studies for JSC (large lift and STS systems analysis)
 - MSFC/DOD IUS/Tug contractor activities (multiple contracts)
 - LMSC Advanced Aeromaneuvering Tug studies for MSFC

B. 3. LARGE SPACE STRUCTURES

Background

The ability to construct and maintain very large structures in Earth orbit is imperative to serious consideration of terrestrial energy supply from space. The microwave transmitting antennae is expected to be in the order of 1 km in diameter and the solar energy collection system may be greater than 50 km² in area. Space structures of this magnitude are unprecedented and require the full application of the space expertise already developed and the extension of that expertise to the necessary new dimensions. The weightless environment of space, however, offers the opportunity to construct such structures without the material handling impairments or mass of structure which an Earth-bound analog of such a construction would require. Studies to date have indicated that the required structural strength may be determined by the loads imposed by construction equipment, crew and the transfer maneuver from low orbit to geosynchronous orbit. Since these loads may be controlled by design, the fabrication of totally adequate ultra-lightweight structures of great longevity may be forecast.

Due to the location of the primary construction site in an orbit of approximately 500 km above the Earth, pre-fabrication of elements on Earth and the employment of (and man controlled) orbital assembly machines is preferable to highly labor-intensive operations. Due to the very low density of the lightweight structural members, orbital machines may be necessary to fabricate, in place, much of the structure from rolls of prepared flat stock and/or other moderate density materials, otherwise, unacceptable penalties on launch vehicle design would result.

Due to the scale and complexity of the construction, man's continuous presence in orbit will probably be necessary to oversee the fabrication and assembly processes, to assure proper alignment and attachment of the component parts, to receive and deploy the construction materials as they arrive from Earth and, finally, to rapidly assess and overcome the inevitable problems which will arise. The Skylab repair experience vividly demonstrated the ability of man, working in space, to use simple tools to correct unforeseen problems which would otherwise cause failure of the entire endeavor. For the construction of

the several hundred space power satellites which may be built in the operational phase, housing, transportation, communications, and an array of tools will be centered at or near the construction site in a low-Earth orbit space station scaled to the tasks. For the early prototype power satellite construction, the orbital cadre will be housed and supported by a space station more modest in scale.

Once the space power satellite, or its modules, are completed in low-Earth orbit, they will be transported to geosynchronous orbit, where final assembly, checkout and activation will take place. As the geosynchronous orbit is more than 35,000 km above the Earth, even more incentive is present to automate the final assembly process than is for the low-Earth orbit construction. Nonetheless, man will almost certainly participate in the high-orbit activities, both during the initial assembly and to preserve, through maintenance, the power generation capability of the satellite for 30 years or more. Thus, it will be advantageous to provide austere but adequate quarters and equipment to permit man's contribution to the harvesting of solar energy from geosynchronous orbit for use on Earth.

Materials used in fabrication of SPS structures must be compatible with the environmental conditions that will be encountered over a long-term period. Selected candidate materials must be low-cost and have low-cost fabrication, and assembly potential. Costs of candidate materials such as aluminum and resin/fiber composites were studied under NAS 3-17835. These studies indicated that in-orbit costs of resin/fiber composite structures will be nearly the same as aluminum. However, it is expected that the low-thermal expansion properties of composites will significantly alleviate structural distortion during periods of varying environmental temperatures. It is thus anticipated that serious consideration will be given to selection of composites for construction of SPS structures. Technological risks are currently greater for composites than for aluminum since little is known concerning the long-term physical and mechanical properties of composites over the anticipated operating temperature range in a vacuum and UV radiation environment.

The design, fabrication, and use of composites over a cryogenic to high temperature range is fairly well understood. Life tests in air over a temperature range of 298° to 590° K have been conducted for periods up to 5000 hours.

Processing techniques for epoxy/fiber composites have been developed to provide extremely low-outgassing characteristics at ambient conditions. Epoxy/fiber composites have been also successfully used for fabrication of vacuum-jacketed dewars. Addition-type polyimide resins may have even lower outgassing characteristics than epoxy resins when used at elevated temperatures (420° to 450° K). Processing of addition-type polyimide resin/fiber composites is not expected to be significantly more costly than for elevated temperature-cure epoxy/fiber composites. Those data indicate that resin/fiber composites (epoxy/graphite and polyimide/graphite) have an excellent potential for use in lightweight space structural applications.

Thermal control will be of paramount importance in the design, construction and operation of both the active and passive elements of the SPS. Construction of modules in LEO will require that the modules, at all stages of assembly, tolerate, with no ill effects, the transition from the sunlit portion of the orbit to darkness each orbit, or about 16 times per day. Due to the very low thermal mass of the ultra-lightweight structure, thermal inertia may not constrain temperature excursions as has been the case in contemporary satellite design.

At the operational orbit, the SPS elements must maintain close alignment in order for the phased-array antennae to function and for solar concentrators to perform properly. Although a GSO satellite is occulted by the Earth less frequently, there is a 44 day interval centered at the semi-annual equinox in which occultation occurs for intervals to a maximum of about an hour. Near the equinox, the GSO orbital plane will be sufficiently close to the solar plane that the network of satellites may occult one another.

The thermal control problem will be complicated, in orbit, by the heat dissipation of the active elements - solar cells, thermal cavities, turbo-machinery, RF generators, and power transmission conduits. Each of the

active elements, in turn, must be assured of reliable dissipation of the waste heat to permit normal operation over a widely-varying load demand, from open-circuit to full capacity. The scale of heat rejection is equivalent to the scale of the power generated - much beyond the contemporary experience. The opportunity of the SPS to radiate the waste heat into space rather than the biosphere carries with it the requirement to reach a new technology plateau in space heat rejection devices.

The functions of attitude control and stationkeeping are required for the SPS to maintain the solar collectors oriented toward the sun and the transmitting antenna oriented toward the receiver and to maintain the satellite at its desired station in orbit. The requirements for these various functions vary greatly. The efficiency of solar collection will not change significantly if the collector orientation varies by a few degrees. The transmitting antenna, however, will require orientation to a small fraction of a degree for efficient transmission of power.

Because of the extreme size and inherent flexibility of the SPS, the attitude control and stationkeeping sensing and actuation must both be distributed in nature rather than located at a single point as in smaller satellites. The control will be exercised over "segments" of the satellites, each segment having its own sensing and actuation. Because the attitude control function must be provided continuously, it will require an automatic system with the loop closed onboard the spacecraft. The stationkeeping function, however, is required at most twice daily and can be initiated by ground commands.

Because the SPS will be highly flexible, as will its individually controlled segments, the dynamic characteristics of the satellite structure must be taken into account in designing the attitude control system. A knowledge of the fundamental vibrational modes, as well as higher order ones, must be obtained and factored into the design of the control system, which will probably be adaptive in nature. Thus the attitude control system and spacecraft structural configuration and design will be highly interrelated. The general nature of the attitude control

and stationkeeping system must be determined in order to permit the generation of basic requirements for the thrusters and other components.

The space operations now indicated to achieve an operational SPS system are also of unprecedented scale. The techniques developed during the previous manned flight program, especially Apollo and Skylab, are directly applicable to the tasks. The manned operations with the Shuttle will greatly expand and enhance this operational experience and make possible the further expansion to the scale inherent to the SPS program. Due to the scope of the endeavor and the expected cost of a man-hour in orbit, the productivity of the orbital crew must reach a new plateau by the use of automation. Much applicable experience in automated space activities has been gained from the NASA and DOD space applications and science programs. Ground control of space activities is also highly developed as a consequence of both the manned and unmanned programs. Therefore, the operations, logistics and supportive functions necessary to the SPS program demand no breakthroughs in science and technology (though it can benefit from them) and the task at hand is considered to pose a complex array of large scale engineering and management problems.

Present SPS concepts indicate a need for large special purpose structures. The necessity of the operational SPS solar energy collectors to maintain an inertial attitude pointing them toward the Sun while the antenna in the center continues to track the ground receiving antennae indicates that large non-conducting, or dielectric bridge structures may be necessary. The relative motion between the collectors and the antennae requires that the total power input to the RF generators be transmitted through a rotary or articulated joints. Concepts exist or can be readily invented to transfer moderate dc power levels across articulated joints such as between the structure and the transmission antenna. The technology associated with transferring 200,000 amps, however, is not well understood at this time.

B.3.a. MATERIALS

Criticality

Varying space environmental conditions will impose severe restraints on selection of structural materials. All materials must be available at acceptable cost and must have thoroughly understood physical and electrical properties, assured availability in the amounts required, and be readily fabricated and assembled into structural elements at a selected Earth orbital attitude. It is expected that periodic inspections need to be made of structural elements to insure retention of required properties, integrity of bonds, etc. and therefore materials must have characteristics that will facilitate inspection and repairs during assembly and in use. Significant outgassing could have a large detrimental effect upon other subsystems; in particular, the RF generation and power transmission elements.

Objectives of Required Efforts

1. Determine materials whose properties are sufficiently known in the expected SPS environment and document those properties.
2. Identify promising materials whose properties are not sufficiently known. Prepare investigation plan that will determine these properties.
3. Perform limited investigations on properties of promising new materials for use in satellite power systems. Identify the composite materials and composite/metal hybrids that appear most promising.
4. Select a prime material for each use element (not just structural) in the satellite power system concepts. If the prime material usage involves non-negligible risk select a backup as well.
5. Develop fabrication techniques for long composite structural elements and waveguides.
6. Develop and evaluate subscale hardware including joining and bonding techniques.
7. Develop data on selected materials exposed to space environmental conditions. Develop processing techniques and equipment for fabricating composite structural elements and application of protective coatings under space environmental

conditions. Develop space processing experimental data.

Recommended Approach

1. Preliminary study to consider materials, in general, for long term use in space. Determine promising materials and identify required work.
2. Conduct trade-off studies to select optimum applications of composites and metallic materials. Input factors - weight savings, low-cost construction, long-term environmental exposure stability, outgassing, thermal expansion compatibility.
3. Select candidate materials and conduct limited thermal aging and compatibility creep, thermal cycling, and outgassing laboratory tests. Apply selected UV and thermal protective coatings.
4. Evaluate bonding techniques and joints for hybrid material combinations.
5. Fabricate and evaluate subscale hardware in latter time frame of activity.
6. Evaluate application techniques for applying coatings on structures under space environmental conditions.
7. Evaluate techniques for fabricating long composite structures for use in waveguides.
8. Evaluate concepts of equipment for fabricating composite structural elements under space environmental conditions.
9. Plan and conduct the appropriate space processing experiments.
10. Plan space environmental exposure tests using subscale hardware for shuttle deployment/retrieval.
11. Conduct materials trade-off studies to provide a sound basis for final selection of materials and protective coatings for construction of supporting structures and waveguides. Input factors in the study will include low-cost construction, long-term environmental exposure stability, outgassing, and the effects of outgassing on system performance, thermal expansion compatibility, assembly techniques, and transporting costs.
12. Conduct materials evaluation experiments to determine the physical and mechanical properties of candidate materials and coatings. Types of tests

to be conducting may include thermal aging, thermal and mechanical fatigue, creep, outgassing, UV and thermal protective tests, emissivity, electrical properties, microwave properties, tensile and compressive strength properties, residual stress studies, and the effect of fabrication-induced flaws on laminate performance. Tests may be conducted to determine the thermal compatibility of composite/metallic material combinations. Studies may also be conducted to examine methods for accelerated outgassing tests of materials in the space environmental conditions.

13. Screen basic polymeric materials with potential for structural or other applications for outgassing characteristics, long-term UV degradation, and thermal/vacuum degradation.

Preliminary Program Estimates

- ① Cost and Schedule (see chart)
- ② Available Technology

The technology for design, fabrication and evaluation of high performance epoxy/graphite, epoxy/Kevlar, epoxy/boron, and polyimide/graphite composite laminates is well established. The state-of-the-art of techniques for laminate analysis is considered adequate for structure design. Analysis programs are currently available that will provide structural designs based on strength, stiffness, residual stress, distortion and creep considerations.

Virtually no technology for composites is available regarding long-term space environmental exposure conditions, particularly for outgassing, UV radiation resistance, creep, and thermal as well as mechanical fatigue effects on strength properties.

- ③ Capabilities and Experience

NASA and Air Force Centers - LeRC, LaRC, and MSFC, in general, have extensive experience with analysis, design, fabrication, and evaluation of composite materials and structures. This also applies to Air Force materials and structures development centers.

MATERIALS (B.3.a.)

Preliminary Program Estimates

Cost and Schedule

	<u>FY76 & TP</u>	<u>FY77</u>	<u>FY78</u>	<u>FY79</u>
- Catalog current materials and properties for baseline SPS application	100K	150K	-	-
- SPS structural element advanced material selection trade studies	100K	100K	100K	100K
- SPS structural element energy requirement analysis	100K	100K	100K	100K
- Laboratory tests of candidate unconventional materials and processes	150K	300K	500K	500K
- Evaluate bonding and mechanical attachment techniques for advanced materials	100K	150K	200K	300K
- Subscale advanced materials (AM) SPS structure	-	100K	500K	1M
- Space environment testing of subscale AM-SPS components	-	-	50K	500K
- Plan and conduct shuttle deployed advanced materials space proof test	50K	100K	500K	1M
	<hr/>	<hr/>	<hr/>	<hr/>
TOTALS	650K	1.05M	2.25M	4.1M

ERDA - The Lawrence Livermore Laboratory has extensive experience in long-term composite testing, evaluation of coatings, and processing technology.

NASA and AF Contractors - A limited number of contractors have extensive knowledge in all aspects of composite technology, particularly high temperature resin/fiber composites.

● Applicable Efforts

Analysis and Design - Comprehensive NASA-LeRC and NASA-LaRC composite analysis studies have been supported for a minimum of five years. Programs have been completed that identify prime factors for design of reliable aerospace composite structures. Computer (NASTRAN) programs are available for the complete design of complex blade-like structures. The programs will provide laminate configurations that meet design requirements for strength, stiffness, torsional rigidity, and low-residual stresses.

Fabrication - The technology for fabrication of epoxy/fiber and polyimide/fiber composite structures is well established. Significant emphasis at LeRC has been placed on the development of easily processed, high temperature polyimide/graphite composites. The fabrication of large aerospace composite structures has been supported by NASA and AF centers.

Evaluation - Test methods to determine many physical and mechanical properties of composites are well understood and are established. New techniques are being developed at LeRC to provide an NDE test method to assess the overall integrity of composite laminates subjected to thermal fatigue tests over a long term period.

B.3.b. STRUCTURE, ASSEMBLY AND FABRICATION

Criticality

This area is self-evident as a "critical area". The basic feasibility of deploying in low orbit structures beyond the capacity of a single launch vehicle has only been demonstrated by the relatively simple docking operations of two complete autonomous modules in the Gemini, Apollo and Skylab programs. An orbital construction project of the SPS magnitude is many times as complex and demanding. It must provide the necessary structural expanse to support the solar energy collection devices, the power distribution conduits, the microwave generators, the phased array transmitting antennae and the necessary supporting subsystems accommodating the necessary pointing requirements and active element alignment. The weight and cost of the space-assembled structure is of central importance to the cost of the electrical power from the SPS system; the structure represents more than 25% of the estimated orbital mass of the SPS. New engineering data must be generated to permit credible weight and cost estimates near the conclusion of the SPT activity, and to identify the assembly and fabrication techniques. The structural assembly must achieve extremely low mass per unit area.

Objectives of Required Efforts

1. Identify the key economic factors of structure, assembly, and fabrication.
2. Determine best structural concept(s).
3. Determine the man/machine involvement in the low Earth orbital fabrication and assembly process.
4. Provide requirements for support systems and modules.
5. Provide requirements for the structural design.
6. Provide preliminary designs for use in systems studies and other subsystem areas.
7. Provide preliminary designs of the payload modules to be placed in low orbit by the HLLV.
8. Provide preliminary design of the SPS modules to be transported from LEO to GSO by the transfer vehicle.
9. Identify the man/machine involvement in the geosynchronous assembly of

modules and activation process.

10. Identify maintenance and logistics requirements of the completed SPS structure and the man/machine involvement in assuring the continued structural integrity and functioning of the SPS structural elements.

Recommended Approach

1. Review results of present MSFC contracts on SPS concepts for key economic factors in the structural assembly and fabrication areas.
2. Continue and expand the preliminary studies of space assembly techniques of large structures underway by JSC and LeRC contracts.
3. Perform conceptual designs including assembly and fabrication techniques for each of the structural assemblies required by the candidate satellite power systems.
4. Perform trade-off studies of candidate design approaches for the SPS structural assemblies with respect to materials costs, processing costs, transportation costs, assembly costs, and maintenance costs.
5. Perform 1g hardware testing of those aspects that can be investigated in 1g.
6. Plan shuttle payloads to investigate the structure, assembly, and fabrication of subscale SPS components in space.

Preliminary Program Estimates

● Cost and Schedule

An in-house NASA effort at JSC, LeRC, MSFC, and LaRC is anticipated.

In addition, a suggested program requiring R&D funding for the definition of SPS structures, assembly and fabrication concepts is shown on the following chart.

● Technology Assessment

This area has been subjected to exploratory low-level studies, but must be characterized as "frontier" technology.

● Capabilities and Experience

JSC and MSFC have extensive experience in the design, development, testing and operation of large space vehicle structures for Apollo/Saturn, Skylab and shuttle.

STRUCTURE, ASSEMBLY, AND FABRICATION (B.3.b.)

Preliminary Program Estimates

Cost and Schedule

	FY76 & TP	FY77	FY78	FY79
- Add special emphasis task to MSFC "Space-based Solar Power" study to identify and work key structural areas	2 @ 50K = 100K	-	-	-
- Augment current LeRC MPTA design study to penetrate assembly & fabrication area	75K	-	-	-
- Perform conceptual design study of photo-voltaic SPS structure, fabrication, and assembly	100K	200K	-	-
- Perform conceptual design study of solar-thermal SPS structure	150K	300K	-	-
- Identify man/machine requirements at LEO & GSO for fabrication and assembly of SPS concept	200K	400K	500K	500K
- Identify requirements for fabrication and assembly support systems	-	150K	300K	600K
- Define technology requirements for large-scale orbital fabrication	100K	200K	200K	-
- Define technology requirements for large-scale orbital assembly, maintenance, and alignment	100K	200K	200K	-
- Plan shuttle flight experiments for development testing of structural concepts	200K	400K	800K	2.0M
- Perform preliminary design of PV SPS structure	-	-	500K	1.5M
- Perform preliminary design of thermal SPS structure	-	-	500K	1.5M
	1.025M	1.85M	3.0M	6.1M

LaRC has extensive structural technology expertise and experience in the ATL project, and is planning an extensive shuttle-based technology program, including structures.

JPL, GSFC, ARC, MSFC and LaRC have extensive experience in the design and operation of unmanned space vehicle structures, including OAO, LST, Viking, the Mariner series, etc.

MSFC and LaRC have on-going structural dynamics analysis programs contributory to the SPS.

MSFC has experience in the large deployable solar area structural area.

B.3.c. THERMAL CONTROL

Criticality

When the SPS passes through the shadow of the Earth or another SPS, it is expected to undergo severe temperature changes. This temperature change can endure the following critical consequences:

- Deformations in the large area solar collector structures and possible damage to individual or chains of solar cells.
- Initiation of significant thermally-induced structural oscillations within the solar collector and microwave antenna structures.
- Potentially unacceptable deformations in the microwave antenna structure, unless countermeasures are taken.
- The SPS active elements (solar cells, thermal cavities, radiators, and RF generators) each pose their individual heat rejection requirement for efficient operation and acceptable life.
- The SPS transportation and habitation elements each pose thermal system requirements for proper function.

Objectives of Required Efforts

1. Understand magnitude of the SPS, transportation and support systems thermal control problems.
2. Develop corrective measures to offset the thermal effects sufficiently to achieve acceptable operations and performance of the SPS, transportation and support systems.

Recommended Approach

1. Define thermal characteristics and behavior of SPS baseline orbital system throughout orbit and occultation periods.
 - Integration of thermal transients loads into structures
 - Temperature - time history
 - Performance analysis based on integrated loads
2. Derive optimum thermal structural design approaches and active thermal controls for SPS

- Materials/combinations
 - Design (thermal storage, radiators, etc.)
 - Selective coatings
 - Fluid loops
 - Louvers
 - Heat pipes as an integrated part of the structure
3. Mission analysis to define nominal and continuous sunlight SPS orbit solar isolation characteristics in LEO, during the transfer and at GSO.
- Mission analysis
 - Weight and propellant requirements
 - Attitude control requirements
 - Transportation requirements
 - Trade-offs and comparisons with baseline systems
4. Modeling Techniques
- Perform modeling feasibility studies to model SPS thermal performance in LEO and GSO at the several levels of assembly.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Capability and Efforts
 - NASA has the personnel and computer capability within the Centers to study and analyze the SPS thermal control effort.
 - Previous studies and thermal testing completed by MSFC are:
 - Skylab
 - Lunar Rover Vehicle
 - Saturn Series
 - HEAO
 - LST
 - JSC has been called upon to do the thermal control design for:
 - Gemini
 - Apollo
 - Lunar Module

THERMAL CONTROL (B. 3. c.)
Preliminary Program Estimates
 Cost and Schedule

	<u>FY76 & TP</u>	<u>FY77</u>	<u>FY78</u>	<u>FY79</u>
- Define thermal characteristics of SPS baseline configurations	200K	-	-	-
- Identify SPS thermal/structural integration issues and approaches	-	200K	-	-
- Perform baseline SPS mission thermal analysis	150K	150K	150K	150K
- Derive active SPS thermal control SRT plan	100K	150K	-	-
- Derive passive SPS control SRT plan	100K	150K	-	-
- Define thermal control and TPS issues and approach of HLLV	-	50K	150K	200K
- Define thermal control and/or TPS issues and approach for transfer vehicle	-	50K	150K	200K
- Define thermal control approach for support modules, including manned transfer vehicle	-	50K	150K	200K
- Develop thermal modeling techniques for SPS system elements	-	100K	200K	500K
- Plan shuttle experiments for active and passive thermal control components	-	150K	300K	600K
	<hr/>	<hr/>	<hr/>	<hr/>
TOTALS	550K	1.05M	1.1M	1.85M

- Spacelab
- Shuttle
- Space Suits Testing
- Ames, GSFC, LaRC, LeRC and JPL have extensive thermal analysis experience of unmanned space vehicle, including those involving largely unknown planetary environments.

B.3.d. ATTITUDE CONTROL AND STATIONKEEPING

Criticality

Existing attitude control system designs and techniques may not be applicable to very large space structures. Current design practice for spacecraft with flexible appendages is to design the control system so its bandwidth is significantly below the frequencies corresponding to the flexural modes. It is highly unlikely that this can be done on the SPS, because of the high degree of flexibility and because the "segments" will themselves be very flexible and will be structurally intercoupled with those around them.

The performance and efficiency of the attitude control and stationkeeping system directly affects (1) structural design criteria to withstand the loads imposed by control element/structural dynamic interactions in the presence of thermal transients, (2) performance and efficiency of the power generation system through the orientation of the solar collectors, (3) the power transmission system performance and efficiency through the orientation of the transmitting antenna, (4) the power receiver requirements through the stationkeeping accuracy, (5) the satellite initial cost through the number and nature of actuators, sensors, and controllers required, (6) the satellite support cost through the efficiency of propellant usage and the cost and reliability of system components.

Present methods are inadequate for analyzing the structural dynamics of ring-connected flexible structure as have been proposed in the baseline SPS design.

Little effort has been expended to date on control techniques for spacecraft which require a large number of sensors and actuators distributed over a highly flexible structure. Thus the nature of the SPS necessitates the study of an area of control system technology hitherto unexplored.

No thruster systems presently exist which can perform to the preliminary requirements established during design of the baseline system. Detailed requirements for the thrusters must be established as early as possible in order to allow development of these components to proceed. These requirements, however, can only be established when the control system techniques and the

nature of the structure and its dynamics have been determined.

The requirements for control during assembly of the SPS are unknown and must be determined.

Objectives of Required Efforts

1. Establish the basic requirements.
2. Determine viable concepts, techniques, and functional designs for attitude control and stationkeeping.
3. Establish requirements for and begin development of the system components, in particular the thrusters.

Recommended Approach

1. The analytical tools necessary to study the control and dynamics of large flexible space structures will be provided by development or modification of existing programs and techniques.
2. Perform an analysis of the dynamic characteristics of ring-connected flexible structures, such as the SPS. This analysis will enable the generation of a mathematical model of the plant to be controlled.
3. Perform a study of various techniques for the attitude control and stationkeeping of the structure so modelled, including a study of the requirements for distributed sensing and activation. From the results of this study, the detailed requirements and specifications for the thruster system and other attitude control and stationkeeping components will be established.
4. Hardware test of the most feasible concept(s). An attitude control system will be designed to perform to the requirements and techniques established during the study phase. Simultaneously, the required thruster system will be developed. The final step should be an overall systems test. This latter will most likely be required to be a flight test, because of the virtual impossibility of satisfactorily testing such a system in a 1-g environment.

Preliminary Program Estimates

- Cost and Schedule (see chart)

ATTITUDE CONTROL AND STATIONKEEPING (B. 3. d.)

Preliminary Program Estimates

Cost and Schedule

	<u>FY76 & TP</u>	<u>FY77</u>	<u>FY78</u>	<u>FY79</u>
- Develop ring-connected structure analysis program	100K	200K		
- Design concepts for SPS attitude control and stationkeeping	100K	200K	400K	800K
- Define component requirements for SPS thrusters	-	100K	200K	400K
- Advanced development of SPS thruster systems	-	-	100K	500K
- Plan shuttle-based tests for SPS - attitude control and stationkeeping subsystems		100K	150K	300K
TOTALS	200K	600K	850K	2.0M

● Technology Assessment

Past technology development is the basis on which to build the SPS technology. Analytical and design tools are developed for flexible spacecraft which have a "tree" configuration. Distributed sensing techniques are well understood for the "tree" configured spacecraft. Ion thrusters systems with specific impulses of $3000 \text{ lb}_f\text{-sec/lb}_m$ are presently undergoing final development phases and are planned to be "technology ready" by FY 1980. A sizeable technology base is available on other types of high Isp electric propulsion. At least one spacecraft (CTS) having a large solar array and significant flexibility is nearing a flight test. This spacecraft will provide information on the dynamic characteristics of flexible structures (tree configuration) in zero-g.

● Capabilities and Experience

Lewis Research Center has experience in the design and testing of high specific impulse (Isp) electric thrusters and in electric thruster research. Also, it has several years experience in research on and development of power processors. In addition, it has some experience in the development and operation of flight tests for these thrusters. It has available and operational computer programs (NASTRAN, UFSSP), which enable the analysis of the dynamics and control of tree-connected flexible spacecraft.

JPL has several years background in the development of analysis tools for the study of the dynamics of tree-configured flexible spacecraft, as well as experience in the development of attitude control systems for interplanetary spacecraft.

Marshall Space Flight Center has experience in the development of large, lightweight solar array structures.

Related past and present efforts - An extended life attitude control system (ELACS) is being designed at JPL. Part of this effort includes detailed analysis of the use of this system for solar electric spacecraft having large flexible solar arrays. This effort is applicable to the study of the SPS attitude control and stationkeeping system.

At the Lewis Research Center, work continues on the development of Electric Propulsion thruster systems. In addition, work is planned on the study of control techniques and systems for spacecraft using these thrusters, and also on guidance and navigation techniques for low-thrust propelled space vehicles.

The Johnson Space Center, in conjunction with Lockheed, is investigating chain-connected flexible structures in support of the Shuttle. In this study, the structures comprise elements connected in a chain, each element in itself having the possibility of being flexible.

B.3.e. OPERATIONS, LOGISTICS AND SUPPORT MODULES

Criticality

As the methods to be employed in the orbital fabrication and assembly of the SPS system are yet to be defined, the operations and supporting systems constitute a large, potentially costly unknown in the SPS cost and risk assessments. The level of manned involvement at LEO and GSO needs to be defined, both for construction of the SPS and for maintaining it in operation for 30 years or more. The support systems which are potentially necessary include manned transfer vehicles, LEO space station (bases?), GSO space stations and an extensive EVA and mobility capability. All of these elements are costly to acquire and to operate. The automation of the fabrication, assembly and maintenance processes is therefore attractive. Concepts are not now defined to achieve this automation. The automatic devices may also be a large acquisition and maintenance expense chargeable to the electrical power produced by the SPS systems. In order to derive good estimates of the SPS power cost, these areas must be explored to the depth necessary to identify concepts, price them out, and reduce the cost uncertainties internal to each of these projects to an acceptable band.

Objectives of Required Efforts

1. Determine an overall operations and logistics plan, including ground operations and maintenance operations.
2. Identify the support modules required.
3. Evaluate the value of various levels of direct manned involvement including the necessary support equipment.

Recommended Approach

1. System analysis of automated and semi-automated/manned operations for assembly and maintenance. Include design complexity, reliability, effects, economic aspects.
2. Perform study of ground operations and logistics and document preliminary plan to illuminate associated costs.

3. Perform trade-off study to evaluate several operational concepts. For each document the logistics plan and the required support modules.

Preliminary Program Estimates

- ④ Cost and Schedule (see chart)

OPERATIONS, LOGISTICS, AND SUPPORT MODULES (B.3.e.)

Preliminary Program Estimates

Cost and Schedule

	<u>FY76 & TP</u>	<u>FY77</u>	<u>FY78</u>	<u>FY79</u>
- Systems analysis of large-scale teloperator deployment	100K	150K	200K	-
- Systems analysis of large-scale EVA for orbital assy	100K	150K	200K	-
- Systems analysis of materials handling, fabrication assy in LEO	150K	200K	200K	-
- Conceptual design of parametric LEO and GSO space stations to support orbital fabrication and assembly	2 @ 400K = 800K*	1.2M	1.2M	1.5M
- Ground operations/support analysis for the SPS system	150K	300K	750K	1.0M
- Communications requirements/capability study for large-scale LEO and GSO activity	100K	200K	300K	600K
- Preliminary design of manned Space Stations for SPS	-	250K	1.0M	4.0M
- Preliminary design of support modules for SPS activation	-	-	500K	500K
- Orbital operations and software analysis	-	100K	200K	
TOTALS	1.4M	2.55M	4.55M	7.1M

*In MSF UPN 981 FY76 draft pad as MSFC study

B.3.f. SPECIAL STRUCTURES AND REQUIREMENTS

Criticality

The electrical power generated by the solar collectors of the SPS must be transmitted across a rotary joint to the microwave antennae, at a current level of 200,000 amperes or more. The transmitted microwave beam must not be blocked, even in part, by conducting structure. The rotary "knuckle" joint of a previous study is a massive device which may be difficult to assemble in orbit. Special structures are anticipated to meet these needs; their characteristics are only dimly understood today. As their development may require new technology to be developed, and their scale and requirements may make them expensive to develop and build, more must be known of these special structures to support SPS program planning and cost estimation.

Objectives of Required Effort

1. Gain and understanding of the requirements to be met by the antennae/collector structural and electrical interfaces.
2. Develop conceptual designs and assembly techniques for the microwave power transmission antenna support structure and electrical conduit.
3. Develop conceptual designs and assembly techniques for di-electric bridge structure.
4. Perform RF beam interference/materials effects tests of candidates di-electric bridge structural elements.
5. Identify SRT plan for SPS special structures.

Recommended Approach

Augment existing studies relating to this area, gather pertinent data on technology applicable, initiate new study and test areas to fill in gaps of needed knowledge.

Preliminary Program Estimates

- Cost and Schedule (see chart)

SPECIAL STRUCTURES AND REQUIREMENTS (B.3.f.)

Preliminary Program Estimates

Cost and Schedule

	<u>FY76 & TP</u>	<u>FY77</u>	<u>FY78</u>	<u>FY79</u>
- Augment MSFC SPS studies to identify special structures requirement	2 @ 25K = 50K	-	-	-
- Augment LeRC MTPA study to include antenna/array support	25K	-	-	-
- Augment JSC orbital assy study to include special structures	50K	50K	-	-
- Perform conceptual design of baseline SPS special structures	-	200K	400K	600K
- Perform RF beam/structure interaction tests (Goldstone?)	150K	200K	200K	200K
- Plan shuttle-based flight experiments of SPS special structure	-	200K	400K	800K
	<hr/>	<hr/>	<hr/>	<hr/>
TOTALS	275K	650K	1.0M	1.6M

C. SOLAR ENERGY CONVERSION

C.1 PHOTOVOLTAIC CONVERSION

Background

The photovoltaic conversion concept for the SPS utilizes a large array of solar cells to convert solar energy directly into electrical energy. The array in this concept is fabricated, launched into low Earth orbit, assembled and deployed there, and then transported into its final geosynchronous position. The solar array is taken as the cells, the lamination (blanket), the mirrors (concentrators), and the bus and support, excluding the basic structure.

For the "Preliminary Technology Assessment", a satellite providing 10GW of power for distribution was considered. This resulted in a 13.85GW output requirement for the solar array. The array under consideration utilized 18% efficient, 50 micron (2 mil) thick solar cells operating at a concentration ratio of 2.06. The mass of the array was 9.76×10^6 Kg of which 8.69×10^6 Kg (89%) was in the area occupied by cells (excluding mirrors, bus and support); the total array area was 63.4 Km^2 of which 30.8 Km^2 (48.6%) was cell blanket area; and the capital cost was \$2,375 million of which \$2,094 million (88%) was for the cell blanket area.

From these figures, it is evident that the array mass and cost are highly dependent on the cell blanket area. In addition, considering the overall mass and costs for the satellite, 36.59×10^6 Kg and \$10,120 million respectively, it is evident that the cell blanket area is a significant factor here as well (23.7% of mass; 20.7% of cost).

The above figures, in comparison to present technology, provide insight to the critical areas for photovoltaic conversion.

Qualitatively, the primary requirements for the solar array, derived from the above, are:

- (a) Extremely low cost cells and assemblies.

- (b) High cell output (high efficiency, concentration, stability).
- (c) Lightweight cell blanket.

C. 1. a. SINGLE CRYSTAL SILICON

Criticality

The SPS considered in the "Preliminary Technology Assessment" requires extremely low cost cells and cell assemblies. The cost for the flight array is \$0.17 per watt output or (for comparison to present flight technology) \$0.31 per watt for the cell blanket area alone, excluding the advantages and costs of concentration. Since present flight solar array costs exceed \$200 per watt for fabrication alone and \$300 per watt to attain a flight ready (fully tested) condition, cost reductions of three orders of magnitude would be required.

Simultaneously, the array considered had a mass of 0.70×10^{-3} Kg/watt. By comparison, the lightest solar array prepared for flight, the Canadian Technology Satellite Array, has a mass of 30×10^{-3} Kg/watt while the most advanced deployable array design (neither built, nor tested, nor flown) has a mass of 9.1×10^{-3} Kg/watt. Thus, mass reductions of at least an order of magnitude are required. Further considerations in this area are: the 0.70×10^{-3} Kg/watt figure was obtained using 18% efficient, 50 micron thick solar cells with minimal shielding under solar concentration. At the present time, the best production cells available for use in flight hardware are 12.5% efficient and 200 to 250 microns thick and, for geosynchronous orbit, use 150 micron thick shields. Also the 18% efficiency is required under solar concentration where the solar cells will run hot (perhaps exceeding 100°C) leading to power losses of approximately 0.5% per $^{\circ}\text{C}$. Thus the 18% value is a lower boundary. (The 12.5% value is obtained at 30°C and reduces to a mere 8.1% at 100°C .)

In view of the above requirements, particularly the reduction in cost by a factor of 1000 and the reduction in weight by a factor of more than 10, the array concept reported in the "Preliminary Technology Assessment" is extremely optimistic and probably not attainable without an awesome breakthrough. On the other hand, since the cost and mass values obtained for that concept represent 23.5% of the total system capital costs and 26.7% of the

mass transported to low Earth orbit, significant deviation from the concept would result in prohibitively high satellite costs. In fact, because of the high impact on mass and cost for the satellite, it would be desirable to reduce the mass and costs of the array further.

At the present time, a capability for terrestrial applications exists at \$20/watt and 3×10^{-3} Kg/watt. Even if it could be used for space application, unacceptably high costs would be encountered. However, significant development efforts are underway for low cost solar cells for terrestrial applications with a 10-year goal of \$0.50/watt. Although mass and space environment are not being considered, the cost does appear to be within the range required for the satellite array. Also, the terrestrial effort includes all aspects, from silicon production through pilot plant operation, so it is anticipated that some of the technology developed will be applicable to the SPS array. Simultaneously, since mass and space environment are not considered, close evaluation (insofar as satellite use is concerned) will be required. For example, an intermediate grade of silicon, between industrial grade and semiconductor grade, material could be developed as a "solar grade" material, suitable for terrestrial use but relatively useless for space flight use because of impurities which significantly affect the radiation susceptibility of the completed cell.

As noted above, present solar cells in the space environment require shielding (glass) for protection, primarily against the radiation environment but also against micrometeorites. In addition, this shield gives protection against ultraviolet radiation and provides a degree of cooling by virtue of reflective filters. The susceptibility of solar cells to the radiation environment is a critical area for the SPS which, after assembly in low Earth orbit, must traverse the Van Allen radiation belts relatively slowly (30 days to one year). Following this, the array is exposed to the radiation at geosynchronous altitude for a lifetime of 30 years or so. Exposure at this altitude alone would result in degradation of 20-25% in power for present solar cells protected by 150 microns of glass. Although the degradation involved could perhaps be

tolerated within the present array concept (it would require a 20-25% additional cost and mass to compensate), the cost and mass penalties due to the shielding would be unacceptable.

Objectives of Required Efforts

In order to bring the above critical areas into a focus suitable for adequate technology and cost projections, the following objectives should be accomplished.

1. A reasonable cost (\$/w) goal for a satellite photovoltaic array must be defined. This goal would be derived from prior developments, present flight technology, and the present technology frontier; and would be built using realistic projections for the technology, incorporating significant, compatible, cost-reducing features such as concentration, passive cooling, etc. The goal would be defined parametrically in terms of attainable limits, probability of attainment, time span required, etc.
2. Similarly, a reasonable mass (Kg/w) goal must be defined along with the inter-relationship between this goal and the above goal.
3. Realistic power-lifetime goals must be determined. These goals would be based upon cell and assembly technology and associated radiation and thermal cycling susceptibility. They would include consideration of radiation degradation due to a variety of transfer orbits and times and of lifetime on station. They would also include consideration of degradation due to extreme thermal cycling during eclipse periods.
4. The risks involved should be determined within the scope of each of the above goal definitions.
5. In order for the above objectives to be fulfilled, an understanding of trade-offs with other subsystem parameters must be obtained. For example, interrelationships between array cost, array mass, and transportation costs or interrelationships between array mass, transfer vehicle thrust, and array degradation must be understood.
6. Efforts to improve solar cells for terrestrial applications must be evaluated both in terms of applicability to the SPS array and in terms of deficiencies

with respect to the SPS application.

7. Required materials efforts must be defined. These would be based upon the results determined in Objectives 1, 2, 3, and 6. They would include interconnects, front and back shield lamination materials, thermal control coatings (high emissivity, ultraviolet reflective coatings), concentrator materials and coating (lightweight material with high reflective coatings), etc.

It should be noted that attainment of the above objectives by the suggested approach and through the estimated program below, although primarily keyed to solutions of problems (resolution of critical areas) for the SPS, will also provide significant results useful in future designs of photovoltaic solar arrays in general.

Recommended Approach

1. Definition of goals and risks (Objectives 1 through 4) and trade-offs (Objective 5) are recommended as a two step contracted approach. The first step would be undertaken immediately in order that the results would be available for earliest possible use of the Satellite Power Team. The second step would be a reiteration after a time span of about three years has elapsed. This would provide an update, incorporating the developments of research projects completed or underway at that time. Although there is considerable merit to using the same contractor to attack all five Objectives, this is not considered mandatory. It would more likely depend on proposals received.
2. Terrestrial, low-cost, solar cell efforts, supported by NASA and ERDA, should be followed by the Photovoltaic Conversion member of the SPT. Areas of applicability to the satellite power station array should be noted and provided for incorporation into the above definition of goals and risks and trade-off studies. Areas of potential deficiency should be evaluated in laboratory tests by either NASA or a contractor.
3. Materials development efforts, determined from the above should be undertaken. Appropriate contractors would be selected to perform this effort.

4. It is anticipated that Items 1 and 2 above will lead to identification of satellite unique problem areas. In addition, it is anticipated that other satellite unique problem areas will be determined independently. These areas should be studied in the depth required.

Preliminary Program Estimates

- ① The program necessary to accomplish the recommended approach is envisioned as follows:

<u>TASK</u>	<u>DURATION</u>	<u>COST</u>
1. Goal & Risk Determination	1 at 1 yr.	\$100K
& Trade-Off Studies	1 at 6 mo.	50K
2. Evaluation of Terrestrial Efforts	4 years	200K
3. Materials Development	3 years	1,200K
4. Unique Problems Study	5 years	700K

- ② Cost and Schedule (see chart)

- ③ Technology Assessment

Lightweight and deployable solar array study and development work has been under development for NASA and the Air Force for more than a decade. Examples of this technology are FRUSA (Air Force/Hughes), Space Station Array (MSC/Lockheed and MSFC/Lockheed), Rollup Subsolar Array (JPL/GE), and SEPS Array (MSFC/Lockheed). Single crystal silicon solar cells have been used for spacecraft power generation since Vanguard, and this technology has become almost routine with advancements being small, few and far between. Present near term efforts are directed towards improved cell efficiency (GSFC, LeRC, JPL) and improving assemblies (GSFC, LeRC, MSFC, JPL). However, such efforts are small in the light of the advancements that are required as described in the criticalities area.

- ④ Capabilities and Experience

There is considerable expertise at various NASA Centers, in the Air Force, and throughout the aerospace industry in the area of single crystal silicon photovoltaic conversion. Experience in lightweight and deployable solar

SINGLE CRYSTAL SILICON (C.1. a.)

Preliminary Program Estimates

Cost and Schedule

<u>TASK</u>	<u>YEARS FROM START</u>					
	0	1	2	3	4	5
1. Goal & Risk Determination & Trade-off Studies	\$100K			\$50K		
2. Evaluation of Terrestrial Efforts		\$50K	\$50K	\$50K	\$50K	
3. Materials Development			\$200K	\$500K	\$500K	
4. Unique Problems Study		\$100K	\$200K	\$200K	\$200K	

arrays is similarly available. However, the expertise required for ultra-low cost, ultra-lightweight arrays is not available and will have to be obtained by extension of present knowledge and experience.

⑥ Applicable Efforts

The effort to develop low cost terrestrial solar arrays by JPL under NASA and ERDA is the most significant, applicable, developmental effort underway. Other developmental efforts sponsored by NSF are in existence. In addition, studies funded by NASA are being performed for JPL and MSFC. Results of these efforts and studies will be incorporated in the above program.

C.1.b. OTHER PHOTOVOLTAIC CONVERSION

Criticality

When considering photovoltaic devices other than single crystal silicon, uncertainties in cost and performance potential are significantly magnified. This results from the fact that, with a few exceptional cases, the stage of development ranges from experimental to pilot production at best. In this atmosphere of uncertainty, the optimism of the proponents of each of the alternatives is unbridled, making it difficult to separate out the state of the technology and the potential and adding the requirement for a realistic evaluation of the present technology to be used as a starting point for assessment.

The photovoltaic conversion concept for the SPS, described in the "Preliminary Technology Assessment", requires cost reductions by a factor of 1000 and mass reductions by a factor greater than 10 compared to present flight application of single crystal silicon technology. Whether these, or reasonably modified, requirements can be met within any reasonable time frame using single crystal silicon technology developments appears highly problematical (see area C.1.a.). In order for the photovoltaic conversion concept to remain viable, then, alternative devices must be considered.

There exists a wide variety of alternative devices, most of which are poorly understood and none of which are well understood because of the early stage of development compared to single crystal silicon. It is conceivable that one or more of these devices could prove superior to single crystal silicon in the long run for the SPS application (not necessarily excluding other applications). In fact there are proponents already who feel strongly that one or another alternative will prove superior. However, conceivability and feelings are totally inadequate bases for technical judgment; factual understanding is required.

Objectives of Required Efforts

The objectives of the required efforts for alternatives to single crystal silicon must, of necessity, start at an assessment level below that for single crystal silicon because of the relative status of the technologies. However,

the objectives must also include sufficient appropriate common objectives to allow both for adequate comparisons of the alternatives with the single crystal silicon devices and for improved technology assessments with respect to the SPS upon completion of the efforts. The objectives to be accomplished are:

1. Determine the potential for photovoltaic devices other than single crystal silicon. This determination would be based upon a survey of alternative devices, past developments, present state of the art, present research goals, theoretical considerations, etc. Alternative devices would include, but would not be limited to, polycrystalline silicon, gallium arsenide, gallium aluminum arsenide, copper sulfide/cadmium sulfide, cadmium telluride, etc. It would also include multilayered cells, multijunction cells, etc. (which are in one form or another, actually variations of the single crystal silicon cell, but would be included because of the comparable state of development).
2. Determine cost (\$/w), mass (Kg/w) and lifetime (radiation susceptibility) goals, and the interrelationship between these goals, for those alternatives found to be potentially promising. These goals would be compared to those for single crystal silicon solar cells.
3. Determine the risks involved in setting the above goals. This would be accomplished in conjunction with the goal determination.
4. Evaluate the solar cell developments resulting from efforts directed toward terrestrial applications in relation to satellite use. This evaluation would include both evaluation for applicability and determination of deficiencies.
5. Provide a study and development plan for any promising alternatives. If accomplishment of the above objectives discloses any reasonably promising alternatives, it is anticipated that concerted development efforts would ensue. It is also anticipated that the objectives for those development efforts would be brought out during the above determinations and evaluations. Based upon these results a study and development plan would be prepared.

Recommended Approach

In order to attain the above objectives, the following approach is recommended:

1. The Satellite Power Team, specifically the Photovoltaic Conversion member, should follow the research efforts directed toward development of alternative photovoltaic devices in addition to single crystal silicon devices. Emphasis would be placed in tracking developmental work directed toward terrestrial applications and in evaluating this work in terms of applicability and deficiencies with respect to satellite use.
2. A contract study should be initiated at an early date to compile, collate, and evaluate the present state of the art and to determine the potential for each of the alternative devices. The former steps are considered necessary because work on the various devices is presently being performed in the form of small scattered efforts by small widely scattered groups. The latter step is, of course, mandatory if the results are to be of value for satellite power considerations.
3. Based upon the above compilation and study of potential, and considering the requirements for the photovoltaic conversion concept for the SPS, promising alternatives should be analyzed in terms of goals (cost, mass, lifetime) to be set and the associated risks involved. These should be compared to those derived for the single crystal silicon option and a determination should be made as to the values of continued pursuit of alternative devices for satellite use.
4. Assuming an alternative candidate or candidates survive the potentials study, the goal and risk determination, and the value determination, concerted research and development efforts would logically follow. The degree and direction of effort required would be estimated by the Satellite Power Team and would be proposed in terms of a study and development plan. Actual research and development efforts are beyond the scope of this section but are noted parenthetically in the program estimates below.

Preliminary Program Estimates

- The program necessary for the recommended approach is envisioned as follows:

<u>TASK</u>	<u>DURATION</u>	<u>COST</u>
1. Evaluation of On-going Efforts, Particularly Terrestrial	3 years	\$ 20K (Travel)
2. Study of Potential	1 year	100K
3. Goal and Risk Determination	1 year	200K
4. Preparation of Study and Development Plan	6 months	N/A
5. (Development of Alternatives)	(5 years)	(10M/yr)

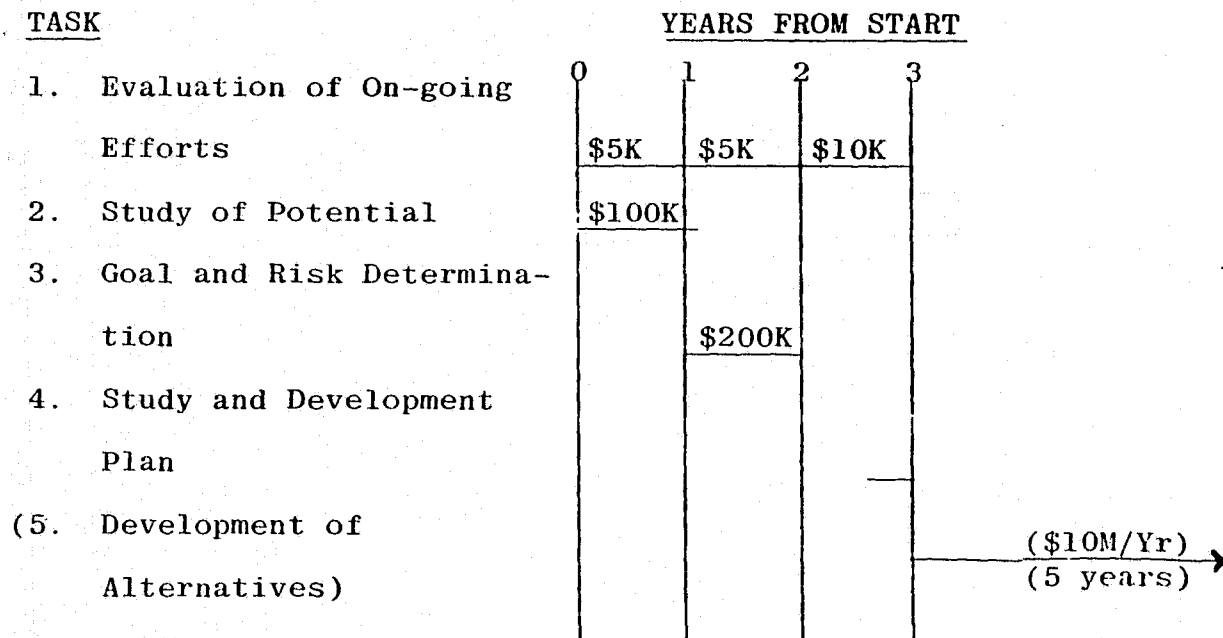
- Cost and Schedule (see chart)
- Technology Assessment

Because of the variety of alternatives involved, prior efforts have been quite diversified. Much of the ongoing effort has been supported by NSF and is being performed by Universities in cooperative efforts with industry. ERDA is sponsoring continuing efforts for terrestrial applications. Some of the effort (not insignificant) has been or is being supported by NASA and the Air Force and is being performed within the aerospace industry. Expertise exists in these diverse areas but, of necessity, has generally been specialized and isolated.

OTHER PHOTOVOLTAIC CONVERSION (C.2.b.)

Preliminary Program Estimates

Cost and Schedule



2. THERMAL CONVERSION

Background

Thermal conversion is concerned with the conversion of solar energy, first to thermal energy, and then from thermal energy to electric energy. The first conversion is done by collection, concentration, and absorption of the incident solar energy; while the second conversion is done either through a dynamic process (e.g. Brayton cycle turbogenerator) or a static process (e.g. Thermionic converter).

The collection, concentration and absorption of solar energy are major factors in establishing overall performance of the system. The concentrators must be lightweight and inexpensive yet efficient enough to produce high temperatures in the absorber in order to achieve high cycle efficiency.

In NASA's space power program the principal concentrator effort was directed toward rigid parabolic reflectors fabricated from magnesium and weighing 0.3 and 1.0 pound/ft² in 6 foot diameter and 30 foot diameter sizes respectively. This technology, although resulting in highly efficient devices, is not applicable to a satellite power system. The concentrators are too complex, expensive and heavy to be considered in an SPS and the materials are not practical for use on a very large scale.

Lighter weight reflectors which are either inflated or spun to form the desired shape have also been under development for a number of years. However, the optical performance of such reflectors is relatively poor particularly at higher concentration ratios. A very limited amount of activity has also been conducted for terrestrial applications with reflectors consisting of films a fraction of a mil thick stretched over a light weight frame system. Techniques of this type may be promising for satellite power system applications but considerable development work remains before firm performance, weight and cost numbers can be obtained.

In general, the absorption of solar energy does not present the same sort of problems as concentration. Cavities with properties closely approaching

ideal black bodies can be readily designed. The principal problems encountered in large systems are associated with removing heat from the absorber cavities and contending with thermal stresses and this technology is not yet in hand.

Studies and hardware development of solar and nuclear - reactor heated energy conversion systems for space application have been underway for well over a decade. The solar conversion program was directed toward low-Earth orbit applications at relatively low power levels (up to tens of kilowatts) and concentrator, heat receiver, conversion system components and complete engines were developed and tested. A nominal 10 KWe Brayton cycle engine has accumulated over 21,000 hours of operation in tests at LeRC at a turbine inlet temperature of 1600°F.

Most of the nuclear reactor space power studies were directed at power levels in the 30 - 500 KWe range for either low Earth orbit or lunar base applications. Through this program a substantial technology base was developed for thermionic and Rankine systems over a period extending from the late 1950's through the early 1970's to complement the solar Brayton activity.

Closed cycle MHD systems have also been considered for high power (10 megawatts and above) space applications. Short term tests have confirmed that attractive power densities can be achieved with the system but overall efficiency projections have yet to be experimentally confirmed. A very low level technology effort is being directed toward efficiency demonstration.

Some of this space program technology may be applicable to a satellite power system, particularly technology associated with materials, bearings, seals, etc. However, the emphasis on low weight and very long life required in the SPS application was not as strong in the earlier space power programs and system power level, even though modular concepts would have to be adopted, and cycle conditions may be quite different for the SPS application.

Closed Brayton cycle technology for ground power applications has also been steadily advancing. In Europe, a 50 MWe engine is scheduled to be put in operation shortly and LeRC is supporting ERDA in the design of a 370 MWe engine for use with a high temperature helium cooled reactor. The emphasis

in ground power applications is on life, reliability, efficiency and cost but the systems are very heavy and, again, the technology is not directly applicable to SPS.

In summary, the selection of a candidate thermal-electric conversion system for SPS cannot be made on the basis of existing information. Conceptual design activities must be undertaken to sort out and select approaches which are promising alternatives to solar photovoltaics.

C.2.a. SOLAR ENERGY CONCENTRATION AND ABSORPTION

Criticality

Solar concentrator/absorber approaches appropriate for a satellite power system application have not yet been demonstrated so that data on costs and mass as well as engineering information including materials selection, configuration, and packaging and deployment techniques are not available.

Objectives of Required Efforts

1. Establish concentrator cost and mass goals and the risk associated with achieving the goals.
2. Establish concentrator life limiting factors and if required develop techniques for refurbishment.
3. Establish concentrator and absorber structural requirements.
4. Establish performance characteristics of candidate concentrator and absorber approaches.
5. Establish scale-up approaches.

Recommended Approach

1. Conduct conceptual design studies.

The conceptual design studies referred to here and in section C.2.b. - Thermal - Electric Energy Conversion - are the same. The costing for the studies appears on the schedule chart for section C.2.b. The viewpoint that has been taken is that the energy conversion and energy collection subsystems are so interrelated that they cannot be separated in the study phase. In fact, the energy subsystem design which evolves will result from an iterative process in which tradeoffs and compromises are made between the collection and conversion techniques.

2. Identify concentrator/absorber concepts for further evaluation.

Promising concentrator/absorber concepts compatible with the energy conversion subsystem will be identified and used as inputs to the conceptual design studies.

3. Analyze and select most promising concepts.

X

4. Perform preliminary design of most promising concepts to obtain performance, cost and scale-up requirements.
5. Experimentally verify concentrator/absorber performance characteristics.

Verification tests will be conducted with subscale hardware with emphasis early in the program on the concentrator and absorber individually and later on the integrated system.

Preliminary Program Estimates

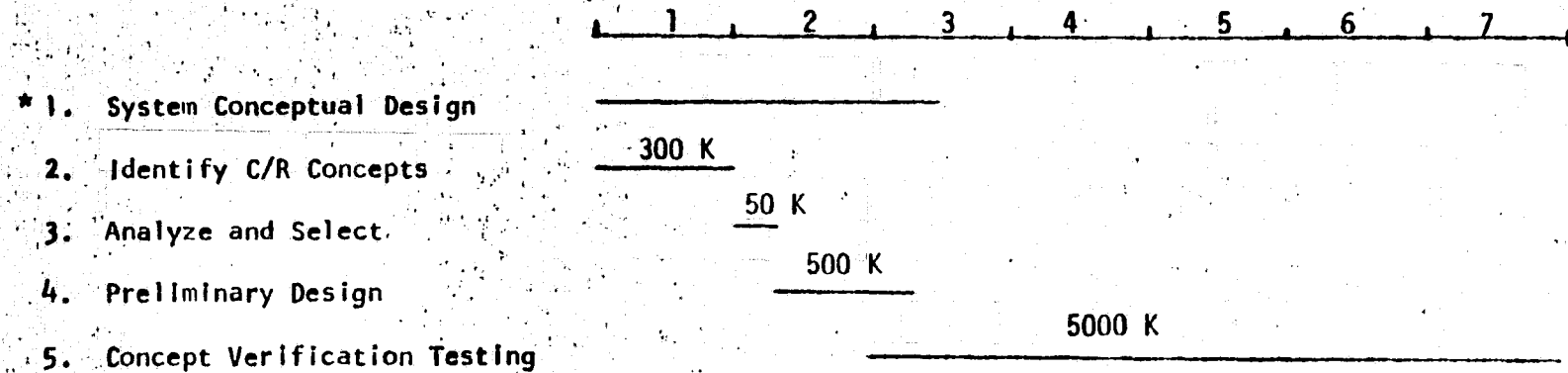
- ① Cost and Schedule (see chart)
- ② Technology Assessment
 - A considerable solar concentrator technology base exists for high performance rigid paraboloids and lighter weight inflatable and spun structures. However, the technology is not directly applicable to a satellite power system because of weight, cost, complexity and/or performance limitations.
 - Some industry-sponsored concentrator technology, aimed at terrestrial applications, shows promise but work is in very early stages.
 - Space power programs emphasized relatively low thermal power absorber technology which did not address the serious heat transfer problems which will be encountered in large systems.
- ③ Assessment of NASA Capability

NASA, and LeRC in particular, has extensive experience in the design, fabrication and evaluation of solar concentrator/absorber systems.
- ④ Applicable Efforts
 - Lewis Research Center is funding ITEK Corporation to investigate the feasibility of large space-based concentrators with diameters up to 30 M for laser applications. However, the present concepts appear to be too complex for an SPS.

SOLAR ENERGY CONCENTRATION AND ABSORPTION (C. 2. a.)

Preliminary Program Estimates

Cost and Schedule



*Funding provided for in solar thermal electric energy conversion conceptual design study efforts.

C.2.b. THERMAL-ELECTRIC ENERGY CONVERSION

Criticality

Data on costs, mass, cycle conditions, module size, configuration for an SPS energy conversion subsystem and packaging procedures are insufficient to base program decisions on.

Objectives of Required Efforts

1. Establish reasonable cost and mass goals for energy conversion subsystem and establish risk associated with achieving goals.
2. Select most promising system(s) concepts for subsequent development efforts.
3. Establish impact of these systems on overall satellite power system.

Recommended Approach

1. Perform parametric and conceptual design studies of candidate solar-thermal systems.

Systems that appear to be candidates at this time include

Brayton cycle, liquid metal Rankine cycle, thermionic systems and MHD systems. The design studies must be conducted in concert with the solar concentration and absorption studies described in section 7A.

2. Select most promising candidate(s) based on overall system considerations.
3. Identify technology requirements for most promising candidate(s).

Preliminary Program Estimates

- ① Cost and Schedule (see chart)
- ② Technology Assessment

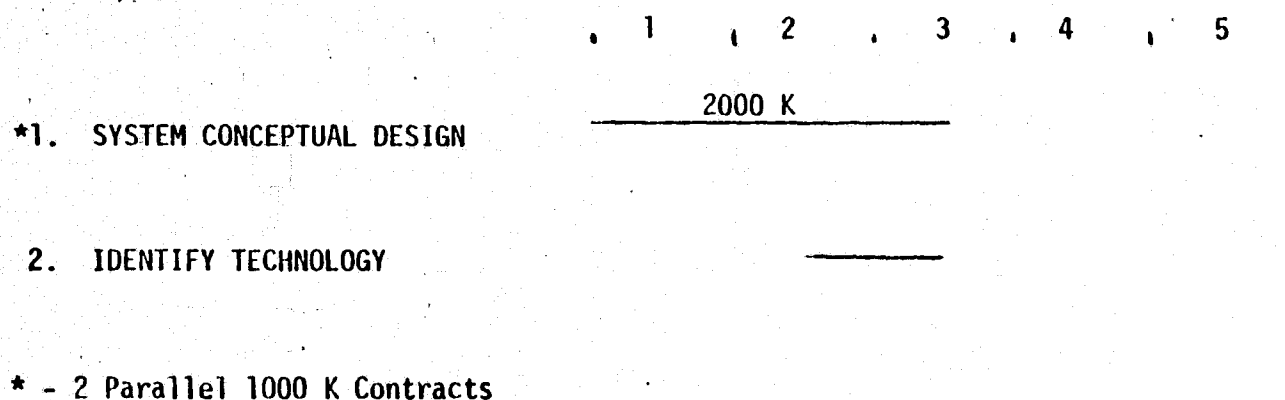
A considerable technology base has been developed in the space power program for Brayton, Rankine, thermionic and MHD power conversion systems. However, as pointed out in the Background section, much of the technology may not be directly appropriate for an SPS application.

- Assessment of NASA Capability
 - LeRC has extensive experience in the design, fabrication and evaluation of power system (Brayton, Rankine, thermionic, MHD,

THERMAL-ELECTRIC ENERGY CONVERSION (C.2.b.)

Preliminary Program Estimates

Cost and Schedule



NOTE: Schedule and cost estimates for the requisite development program have not been included since they differ markedly from system to system and are therefore dependent on selection of system concept(s).

thermoelectric) components and complete Brayton cycle engines.

- JPL has extensive experience with thermionic systems and liquid metal MHD systems.

● Applicable Efforts

- Brayton Cycle:

LeRC supporting ERDA on high temperature gas reactor-gas turbine program.

EPRI supporting open cycle gas turbine studies for solar terrestrial energy conversion applications.

- Liquid Metal Rankine Cycle:

No R&D efforts currently being supported.

- Thermionic System:

ERDA and NASA supporting R&D programs directed toward terrestrial applications.

- MHD System:

NASA and ERDA conducting inert gas MHD generator programs. ECAS (Energy Conversion Alternatives Study), jointly funded by ERDA, OMB and NASA with in-house LeRC support is considering Brayton, Liquid Metal Rankine and MHD Systems for coal fired conversion applications.

3. DISTRIBUTION

C.3.a. High Voltage - Plasma Interactions

Background

In the design of a satellite power system high power, high voltage systems will probably be used in an effort to achieve high efficiency and low weight. These systems can conceivably be simplified by exposing the high voltage surfaces to space to self-radiate the heat from system inefficiencies or to avoid the weight of insulation.

This possible exposure of high voltage surfaces requires that consideration be given to the possible interactions between high voltage surfaces and the space plasma. The interactions that must be considered in design are the current flows between surfaces at different voltages immersed in the space plasma, the charge stored on insulator surfaces (i. e., spacecraft charging) and plasma initiated discharges. These interactions and their impact on the high voltage, high power subsystem performance must be understood and accounted for in order to guarantee high performance and long life to a satellite power system.

These interactions depend upon the electric fields established by the high voltage surface in the surrounding environment. The environment of concern is the low energy plasmas or the particles with energies in the range of volts to kilovolts. The higher energy particles will not be attracted by the kilovolt levels anticipated in the satellite power system. The low energy environment is not fully understood nor mapped especially at synchronous altitudes. It was only at the beginning of the seventies that the kilovolt energy plasma clouds that have given rise to the environmental charging phenomena were discovered. This differential charging and the subsequent discharge are believed to be the cause of the numerous electronic anomalies reported by the satellite in synchronous orbit and is a possible cause for the failure of an Air Force communications satellite.

There has been ground testing of the space plasma interaction with high voltage surfaces. The results have indicated that there is a strong interaction even at voltages as low as a few hundred volts. However, in all ground test facilities, there

is always the question of the accuracy of the space plasma simulation, the influence of the tank walls and the interaction of the test surface with the plasma source. These factors can influence the test results and can be resolved best by a space flight experiment.

In an effort to resolve some of these difficulties, a flight experiment SPHINX (Space Plasma High Voltage Interaction Experiment) was attempted but was lost after failure of the launch vehicle. Two other flight experiments have been proposed. The proposed SPHINX B/C (Space Plasma High Voltage Interaction Experiment) mission would investigate the interactions, in space, between the plasma and a variety of surfaces biased to ± 16 KV. The information obtained from this flight could be used to calibrate a ground facility for additional testing at the higher voltages anticipated for the satellite power system. The Air Force SCATHA (Spacecraft Charging At The High Altitudes) mission would investigate the tendency of spacecraft surfaces to charge in a plasma environment and can obtain information that would be useful for the high voltage subsystem design. There is no planned mission to investigate plasma interactions at both high power and high voltage.

Criticality

This area is critical because there will be an interaction between the plasma environment and any high voltage surface exposed to that environment that will influence the design and operation of the electrical systems of the satellite. Because the interaction effects vary with geometry, materials, etc., there will be a considerable effect on the spacecraft configuration, the materials selected, the design parameters, the efficiency and possibly the mode of operation. Under conditions of arcing, severe transient conditions will be imposed on electronic components that could limit their life.

The attitude control and stationkeeping systems will utilize electric propulsion systems. These systems will eject plasma particles into the region around the satellite and change the local density. This can have an influence on the

interactions between the satellite systems and the environment and these must be evaluated. Furthermore, in the event of spurious discharges in this satellite due to differential charging, the resulting radiation is strong enough to interfere with the sensitive electronics of the more advanced attitude control/stationkeeping systems.

The selection of the prime power generating system will also depend on the interaction of high voltage surfaces with the environment. If a high voltage solar array is desired, then the array interactions with the environment must be controlled in order for the system to function.

Although tests conducted to date indicate that it may be possible to reduce the extent of the interaction through control of spacecraft geometry and materials, much more knowledge is required in order to assure that the interaction effects can be brought to an acceptable level.

Objectives of Required Efforts

The objectives of this phase of the program are to obtain the engineering data that is necessary to design electrical systems that can be exposed to the space environment over a wide range of system operational voltages and of environmental conditions.

Recommended Approach

1. A ground based experimental program to be conducted to determine the extent of ambient plasma interactions with the surfaces that will be used in the proposed high voltage systems. The tests will be run at the proposed voltage levels and under the simulated environmental conditions. The data will be used in an analytical program to determine the electric fields in the plasma due to the high voltage surface. Geometric factors and surrounding boundary conditions will be investigated.
2. The results of this experimental program will be used to generate an analytical model that will be used to predict the interactions for a spacecraft operating in the space plasma environment. Techniques to minimize the interactions that are suggested by the analytical results will be verified by experiments.

3. Conduct space experiments to measure all environmental parameters in the orbit of interest, to verify the plasma interactions, and to establish benchmarks for additional ground testing. This latter point will allow for the calibration of a ground facility to remove the test result uncertainty. The results of the flight experiments will then be used to conduct additional testing as required.

Preliminary Program Estimates

- ① Cost and Schedule (see chart)
- ② Technology Assessment

Research in the plasma interaction studies has been underway for the past five years. These studies involved both in-house work at LeRC and contractual studies. As a result of these investigations, a flight experiment, SPHINX (Space Plasma High Voltage Interaction Experiment), was designed and built. Unfortunately, this satellite was lost in the Titan-Centaur proof flight.

- ③ Capability Assessment

The capability to perform this research exists with the NASA. The study of the interaction between high voltage surfaces and a plasma is currently underway although limited to voltages of 20 kilovolts.

- ④ Applicable Efforts

The environmental charging investigations are now getting underway under a joint NASA/AF program. This is a four year program to conduct ground experiments to define the environment and to study the environmental charging phenomena. In this area there are two flight programs: the Air Force SCATHA program and the proposed new start for the SPHINX.

HIGH VOLTAGE - PLASMA INTERACTIONS (C. 3. a.)

Preliminary Program Estimates

Cost and Schedule

<u>TASK</u>	<u>FY</u>	76	77	78	79	80	81
GROUND BASED INTERACTION STUDIES					2½M		
		←	(1)	→			
DESIGN TECHNIQUES AND MATERIALS DEVELOPMENT					2M		
		←	(1)	→			
FLIGHT EXPERIMENTS			2M			3M	
			←	(2)	→		
		←	(3)	→			
DESIGN REQUIREMENTS AND CONSTRAINTS						1M	

- (1) Current combined funding in these areas by NASA OAST and Air Force is planned at 1-2M per year.
- (2) Sphinx B/C flight experiment FY77 new start requested to NASA OAST AT 6M plus launch vehicle.
- (3) Scatha flight exp. to be funded by Air Force at 15M plus launch vehicle.

C.3.b. Power Processing for Photovoltaic Power Generation

Background

A photovoltaic power source for the SPS would involve the use of multi-gigawatt solar arrays to supply the required electrical power for the primary load, viz. 20-40 kV microwave power generation tubes, plus other secondary low voltage loads associated with control, telemetry and various housekeeping functions. The power processing system between the solar array and loads serves to appropriately change voltage waveforms, control and regulate load power and provide protection as may be desirable for source, processor and loads.

Conventional spacecraft power processing systems generally consist of a separate piece of hardware between a relatively low voltage (~ 50 -100) solar array bus and loads as determined by spacecraft needs. The approaches to power processing for the SPS, however, might include other than conventional options. It may be desirable from weight and cost considerations to provide as much of the power processing as possible by use of the high voltage solar array concept with integral regulation provided by shunting switches mounted directly on the high voltage-configured solar array. This concept is presently under development by LeRC for potential application to directly supplying power for 10-15 kV TWT's; 3 kW, 1000 V 30-cm ion thrusters; and other loads. The question of how high in voltage the SPS solar arrays may be operated from the plasma interaction standpoint (see section C.3.a.) is unanswered, however. It is apparent that allowable array configuration voltage levels will impact heavily upon conceptual designs for the SPS power distribution system including power processing.

The use of medium voltage (~ 1 kV) solar arrays with conventional power processing to supply both the very HV tube loads as well as other load requirements should also be considered as an alternative to integral regulation high voltage solar arrays. This approach would require a careful examination of circuit and component limitations to define the degree of technology extension which may be required to meet the high power and voltage levels for the SPS system.

Optional photovoltaic power processing systems may be intimately concerned with solar array design and configuration, particularly if the use of the integrally regulated array is shown to be advantageous in terms of weight, efficiency, lifetime and cost elements.

Criticality

- Much higher voltage and power levels than currently in use are required.
- Approach used for power processing is a significant factor in total power generation system weight and cost.

Objective of Required Efforts

1. Determine present capability and reasonable goals for
 - Efficiency
 - Mass (Kg/W)
 - Lifetime
 - Cost (\$/w)
2. Identify problem areas to be expected in development.
3. Select prime and backup approach based upon conceptual design.
4. Identify areas of impact on overall satellite power system design.
5. Initiate development of appropriate prime and backup hardware.

Recommended Approach

1. Conduct system concept definition studies. The studies are to include potential trade-offs in weight, efficiency, lifetime and cost for possible approaches to power generation/processing/distribution.
 - High (40+ KV) voltage solar array system with integral regulation
 - Medium (KV) voltage solar array system with conventional power processing
 - High voltage solar array with solar concentration
 - Medium voltage solar array with solar concentration and conventional power processing
2. Conduct preliminary evaluation of power processing impact on overall SPS power system design.

3. Demonstrate feasibility of key power processing elements.
 - Develop improved electronic components with higher power and voltage ratings
 - Develop electronic circuit approaches
 - Develop high power space switchgear
4. Evaluate and document power processing impact on key power generation system drivers with revision of early estimates.

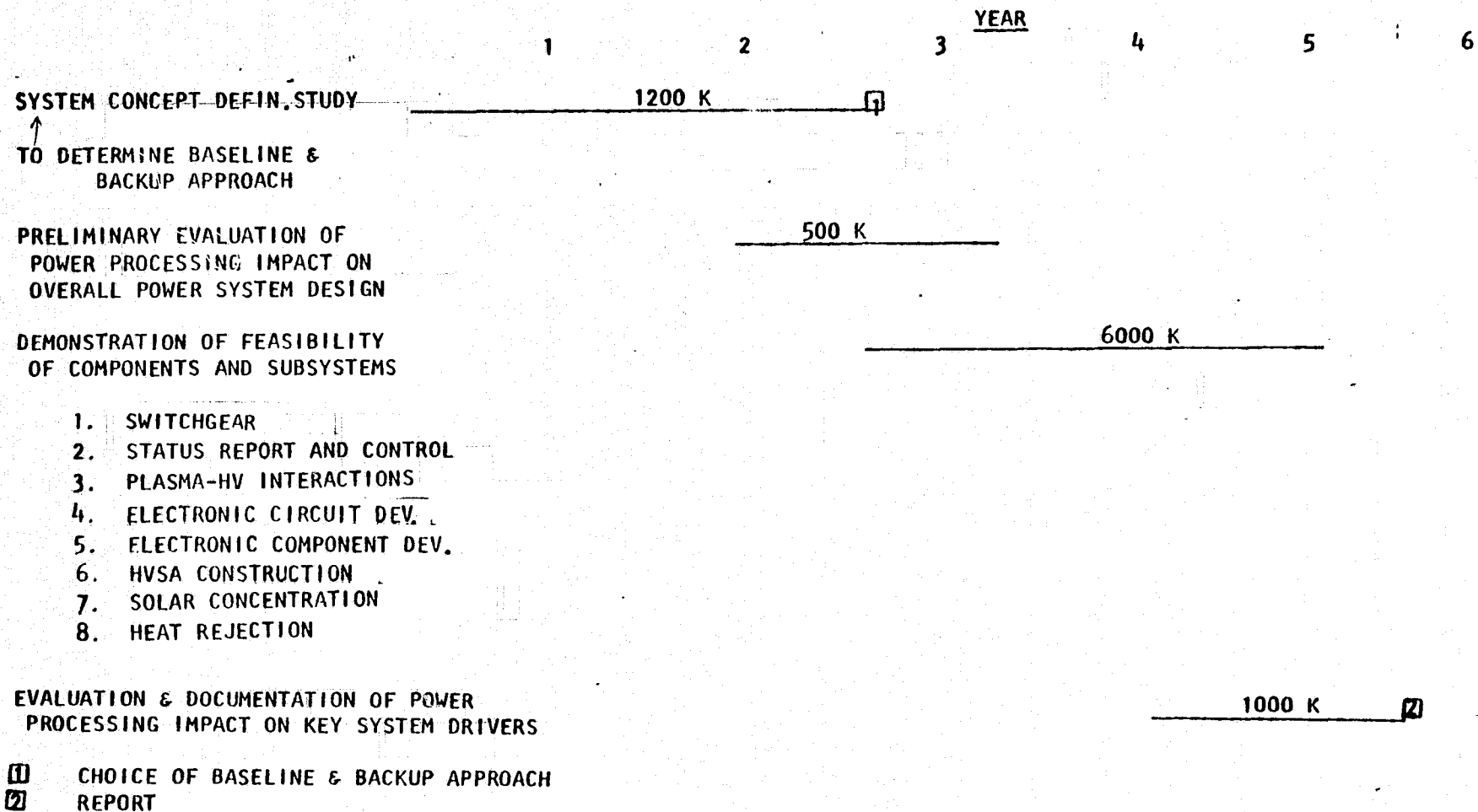
Preliminary Program Estimates

- Cost and Schedule (see chart)
- Technology Assessment
 - Present technology based upon conventional approach with multikilowatt - 1000 V output capability on 100-400 volt input bus.
 - Major extension of component and circuit capability in terms of power and voltage (40 + kV) level required.
 - High voltage solar array concept with integral power processing not proven for space use at required high (up to 40 + kV) voltages.
- Assessment of NASA Capability
 - Number of NASA centers have power processing capability.
 - High voltage solar array with integral regulation concept being developed at LeRC.
- Related Effort
 - Multikilowatt power processor development program at LeRC for Solar Electric Propulsion System program.
 - High voltage solar array with integral regulation development program at LeRC.

POWER PROCESSING FOR PHOTOVOLTAIC POWER GENERATION (C. 3. b.)

Preliminary Program Estimates

Cost and Schedule



C.3.c. Power Processing for AC Generator

Background

The use of a solar-thermal-mechanical cycle instead of a photovoltaic power source for the SPS would involve a turbine - alternator to produce AC power at a level appropriate to the primary high voltage DC load, i. e. the microwave generation power tubes. This AC power needs to be transformed, rectified, and filtered. The approaches to ground-based rectification are well established but consideration needs to be given to extension of this technology to high power space application with emphasis on reliability, weight, efficiency and cost.

The power processing requirements for the primary HV tube loads as well as for various secondary lower voltage loads needs to be identified in terms of the weight, efficiency, lifetime and cost elements for the complete system of AC generator source and transformer/rectifier/filter modules. Then improvements of these four system characteristics will be developed to meet the requirements.

Criticality

- Proper space environment operation of power processing is necessary for system feasibility since power from the generator must be transformed, rectified, and filtered for tube use.
- System lightweight, high efficiency and long life must be maintained.
- Ground based power transformation, rectification, and filtering is well developed. This technology must be extended to high power space applications.

Objectives of Required Efforts

1. Determine present capability and reasonable goals for
 - Efficiency
 - Cost (\$/w)
 - Mass (kg/w)
 - Lifetime
2. Identify problem areas to be expected in development
3. Select approach based on conceptual design
4. Identify areas of impact on overall satellite power system design
5. Initiate development of appropriate hardware

Recommended Approach

1. System concept definition study, including trade-off between AC generator output voltage and power processor voltage transformation prior to rectification.
2. Preliminary evaluation of power processing impact on overall system design.
3. Fabricate and test transformer/rectifier module.
4. Complete evaluation of efficiency, cost, mass, and lifetime for satellite power system application.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Technology Assessment

Present ground-based technology requires extension to space type hardware, with emphasis on weight, efficiency, reliability and cost.

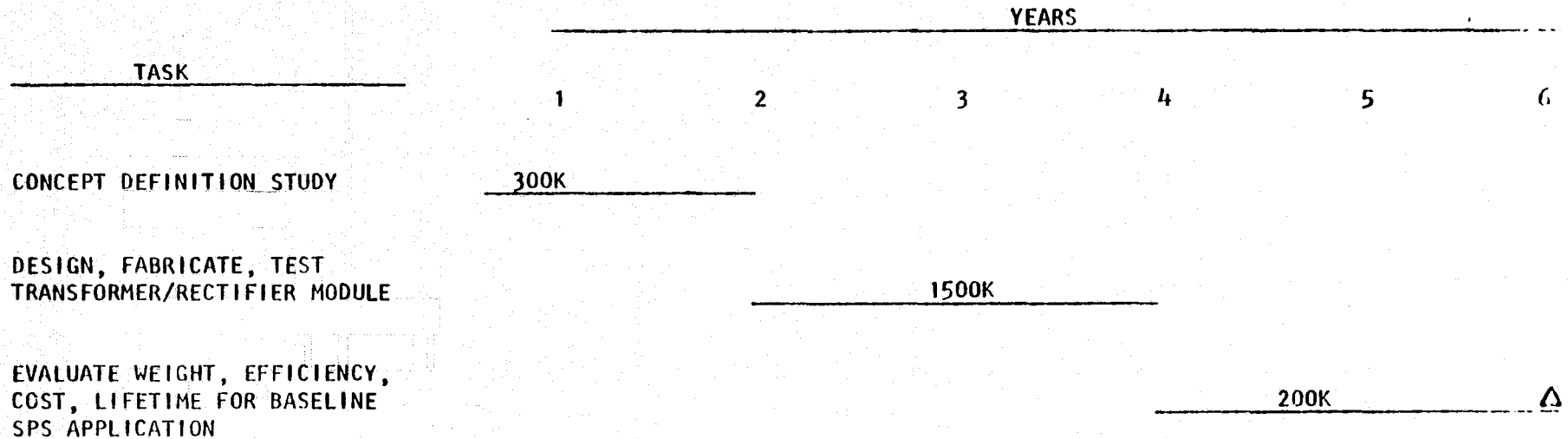
- Related Efforts

None known for high power space application.

POWER PROCESSING FOR AC GENERATOR (C.3.c.)

Preliminary Program Estimates

Cost and Schedule



△ FINAL REPORT

D. MICROWAVE SYSTEMS

D.1 DC-RF CONVERSION

Background

The DC to RF conversion function is one of the intermediate links in the system chain of energy transmission from sunlight to the output buss bar on Earth. The pass through efficiency or conversion from DC input to RF output is thus the paramount design factor for the converter and the resulting device design and performance is strongly influenced by the conditions of the adjacent links in the chain.

The converters are microwave devices (operating wavelength approximately $1/3\text{m}$) and as such the small resonator dimensions require cooling for proper operation at the high power levels required for the system.

A single converter is impractical and thus many converters will be distributed across the surface of the radiating antenna. Consequently, there are subsystem design tradeoffs regarding passive or active cooling schemes, device power levels and quantities and packing density.

System requirements for tapering the microwave power density across the transmitting antenna aperture must be accommodated by either having a stock of converter devices with variable power levels, or a family of converters with a range of power levels, or by the use of a single power level device coupled with antenna elements having a range of different couplings per unit of area. The latter is probably the most efficient method.

System requirements for variable power transmission levels for sources or load following, turn on or off sequences, maintenance area isolation, system testing or safety reasons can be accommodated by either switching converters on or off or by providing variable output of all devices. The former method changes beam shape and sidelobe level and position while the intensity changes. The latter method would maintain the beam shape and sidelobe position. Operationally, the latter method is cleaner from the RFI and safety point of view, but the efficiency may be compromised in order to supply that version

of a variable power capability.

Unless positive load management or purposeful isolation is designed into the load presented to the converters, then changes in load conditions will reflect adversely into the device performance. A system tradeoff exists between the ground based collector reflected power directional characteristics (and thus collection efficiency) and the space based converter stability and performance (and thus conversion efficiency).

Because of the critical design operating parameters associated with high efficiency operation, a host of auxiliary instrumentation and controls will be required to monitor and react to load and input conditions--reflected power and drive signal level monitors, input to output phase shift and input power conditioning and regulation. The degree and thus cost of the above is a function of the system and subsystem requirements.

Planned maintenance of the DC to RF conversion function via scheduled device replacement and refurbishment or built-in component replacement may well be necessary for a design lifetime up to 30 years.

In addition to high conversion efficiency and long life, the devices must possess very low RFI output and good phase stability. The device operating environment must be defined in detail and the above characteristics must be quantified and a balance struck between computing characteristics during a device and system requirements development phase since no current single device possesses the above characteristics.

Criticality

The DC to RF conversion function is critical to satellite power systems since the conversion efficiency directly influences the solar collector size. Because a prototype device does not exist that incorporates all of the required operational performance characteristics, it is not possible to accurately determine the conversion efficiency. Estimates of performance can be made based upon extrapolations of existing microwave devices, but until the operational environment is detailed and candidate device designs developed and measured, the uncertainty

in the performance estimates will be large. Accordingly, the collector size must be large in order to bound the uncertainties.

The power transfer efficiency is also a function of how well the microwave beam is formed or focussed and maintained. Consequently the phase stability, both long term and short term of the microwave devices has considerable influence on the power transmission link transfer efficiency and thus the input solar collector size.

The "electropolitical" acceptance of microwave beamed power satellite systems will be a function of how well spurious and harmonic signals can be managed. Filtering requirements to accommodate particular national or international operational agreements will affect the conversion efficiency performance of the devices.

The lifetime of the devices must be determined by testing and extrapolation in order to plan maintenance if required.

Objectives of Required Efforts

1. Determine detailed device operational environment and interfaces: atmospheric pressure/ionosphere/charged particle flux densities/magnetic fields/thermal impedances/thermal capacities/supply voltage regulation/supply impedance/mounting forces/attitudes/RF impedance levels and stabilities/monitor instrumentation/signal sample points/current monitoring bypassing and feedthrus/control electrodes/signal distribution/connectors/flanges/RF shielding/personnel protection shielding/assembly guides.
2. Determine system and subsystem performance requirements: efficiency/phase stability/life/cost/weight/size/RFI levels/power levels/identify any requirements for variable power levels, gain, linearity, saturation characteristics, modulation, bandwidth/required taper based upon biological and RFI, phase error and device failure-maintenance rates.
3. Determine device capabilities: build efficiency model/measure noise/measure power supply, RF drive, antenna interface characteristics/measure thermal and life characteristics.

4. Compare performance results and system requirements: process statistics of measured data, review tradeoffs.
5. Project costs and performance: examine mass manufacturing and testing in space/maintenance schemes.

Recommended Approach

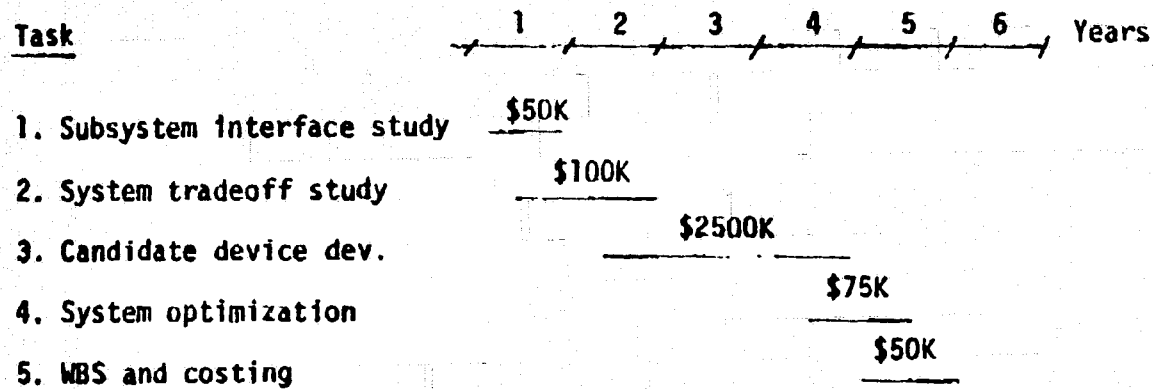
1. Perform preliminary--conceptual design sketch exercises with adjacent subsystems--identify tradeoffs, determine interfaces and tolerances.
2. Participate in overall system optimization tradeoff studies and set converter requirements based on estimated performance capabilities.
3. Write specifications and objectives for and let and monitor candidate device design, development and test contracts.
4. Re-do system optimization tradeoff studies based on measured device performance results.
5. Develop detailed work breakdown structure and estimate resources for each item to arrive at cost data.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Available Technology

Only the crossed field devices such as magnetrons and amplitrons or linear beam tubes such as the klystron appear to be potential DC to RF converter devices at this time. The crossed field devices suffer from low gain and much noise yet they have high conversion efficiency and potentially can work without life limiting externally heated cathodes. The klystron suffers from low conversion efficiency and a life limited cathode yet it possesses a clean output spectrum, has high gain and is adaptable to a thermally efficient high temperature radiation cooled collector. The crossed field device is thermally limited under conditions of passive cooling by maximum allowable magnet temperatures. The klystron can be electrostatically focussed without requirements for magnets, however a multiple cathode electron gun may be necessary to overcome cathode life limitations. Controlled second harmonic injection

DC-RF CONVERSION (D. 1)
Preliminary Program Estimates
Cost and Schedule



in the klystron with possibly multiple depressed collectors could improve the klystron efficiency.

● Capabilities and Experience

JPL has developed the free world's highest powered S-band CW total transmitter systems for the deep space network. Also, S-band tube and transmitter development program from spacecraft 10 W TWT's and 100 W electrostatically focussed, radiation cooled collector klystrons to earthbound 450 KW klystrons have been successfully managed. A development program for a multiple cathode replacement device (MEG) was nearly completed before funding priorities were changed.

LeRC has extensive capabilities to also design and manage tube developments. Flight hardware was recently delivered for the world's most efficient TWT, 200 W, 12 GHz.

JSC in the Apollo program managed the successful application of 25 W S-band amplitrans in the Apollo Communication System.

The Varian Co. is the world leader in klystron development as Raytheon is foremost in amplitrans development.

High power test facilities for transmitters exist at the Venus Station at Goldstone, CA. LeRC, JSC and JPL all have space simulation chambers large enough to test fractional modules of space version transmitter-antenna models.

● Present Efforts

LeRC is managing a Raytheon contract on microwave transmission system studies (NAS 3-17835). A 5 KW radiation cooled amplitrans conceptual design is completed. A 40 KW radiation cooled, magnetically focussed klystron concept version is in process. Depressed collector analytical modeling is being done at LeRC.

D.2 TRANSMISSION PHASE CONTROL

Background

The function of the transmission phase control system is to determine and maintain the correct individual phases of all the antenna phased array elements.

A phase control system is necessary to fine point the K beam because the spacecraft mechanical attitude control pointing system cannot keep the very large diameter transmitting array point accurately enough to maintain the beam continuously on the earthbound target. Also, since the radiating surface of the approximately one kilometer diameter antenna cannot be maintained to the required degree of curvature within a tolerance of approximately 2mm, then the surface is segmented into portions that are small and stiff enough to maintain the quite small structural error. The RF electronics system takes over from that point and fine controls the individual radiating element phase to keep it in proper step with a reference element.

In addition to phase errors caused by mis-pointing and differential deflection of the antenna structure, another source of phase errors is due to propagation path variations caused by, for example, charged particle density changes or due to having the RF beam look through a non-homogeneous dielectric support structure.

A technique for re-directing the beam in the appropriate direction involves launching a pilot signal from the receiving location on the Earth, providing the propagation path remains relatively stable over a round trip RF path time period.

RF electronics aboard the space-borne transmitter elements are designed to compare the phase difference between the received pilot signal and the transmitted power signal and to perform a conjugating function that locally corrects for the locally detected phase error. (That is, a received phase lag must become a phase lead of the same magnitude upon re-transmission.)

Since the phase conjugation cannot be accomplished with the same pilot and power signal frequency, the pilot must be offset in frequency from the transmitted power signal. Thus, frequency separation via filtering and conversion is

required in the phase conjugating scheme.

However, the conversion reference signal must also be constrained to be globally in step with its neighbors in the array. This requires that a reference phase signal be distributed to all transmitting elements. The major problem in a very large retrodirective phased array is how to perform the phase reference distribution across a surface that is changing dimension.

The pilot signal will further have to be coded to prevent unauthorized pilot beams from directing power in unwanted directions.

Criticality

The satellite power system RF beam efficiency, in terms of pointing, focussing and maintaining the maximum RF power density on the receiving array, is a function of the overall phase control system error--including any non-compensated propagation path phase errors. Thus, the transmission phase control accuracy is one of the system efficiency contributing factors that determines the solar collector size.

A theory exists for a phase reference distribution system to operate over a changing structure but its accuracy has yet to be demonstrated on such a large scale or for up to 30 years operational lifetime.

The pointing accuracy and rms phase error also determine the ground based RF collector diameter, any guard ring diameter, and the sidelobe maximum levels which affect the biological and RFI performance of the system.

In order to achieve the required small magnitude of allowable phase error that will be necessary in order to maintain a very high beam efficiency, specially tailored or selectively matched components will be required. Precision supporting equipment, extensive use of feedback control systems to achieve nearly identical component phase performance characteristics and precision monitoring instrumentation coupled with frequent maintenance or alignment routines will be required to keep phase errors within design limits. The degree of accuracy of the above requirements and thus cost of the above is a function of the system beam efficiency requirement.

Objectives of Required Efforts

1. Demonstrate an adequate phase reference distribution scheme: path length change compensation accuracy/aging characteristics/required alignment maintenance.
2. Determine required system operational characteristics: beam efficiency/rms phase error/allowable beam wander/structure, ionosphere, and atmosphere phase error correction/identify any multibeam capability requirements in service several RF collectors/identify any required variable focus capability to assist in load following, start-up, shut-down, or variable intensity safety capabilities/investigate multiple pilot locations in RF collector area for fail safe backup or operational convenience to move beam center for bias offsets or to speed up rain drying or to speed melting snow removal/set required RFI level and directional constraints and biological constraints, translate into allowable sidelobe levels, do tradeoffs with taper and percent element failure and guard ring diameter/determine system SNR's/frequency ratios/diplexer loss, isolation, phase stability/AM to PM conversion and other active device phase induced changes, drive, supply voltage, load impedance, and temperature changes/array radiator element size/de-coder performance/signal monitoring points/system VSWR's/shielding, grounding, and spurious signals.
3. Optimally allocate allowable phase errors among contributors.
4. Obtain operational experience on system stability and security.
5. Project costs and performance for phase control system.

Recommended Approach

1. Complete circuit design analysis of phase reference distribution scheme, fabricate and test breadboard models.
2. Participate in overall system optimization tradeoff studies in order to set preliminary control system requirements based upon estimated performance capabilities.
3. Model and analyze entire phase control system in order to access operating tolerances and to optimize control system performance.

4. Design, fabricate and operate a large ground demonstration model to verify performance and maintenance of small phase errors, security, pointing, beam efficiency, and low sidelobe levels. Demonstrate safety performance during start-up, shut-down, and other transient conditions.
5. Develop detailed work breakdown structure and estimate resources to arrive at cost data based upon demonstration model performance.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Available Technology

Concepts and models of small diameter (in wavelengths) retrodirective phased arrays exist and have been developed and analyzed. However, concepts and demonstrations of large diameter systems are few. JPL and the Valley Forge Research Center of the University of Pennsylvania are known to be active in the field. Performance analysis techniques need consolidating.

A significant amount of related technology in phase commanded arrays has been done by Bell Labs, Sperry, RCA, Texas Instruments, Raytheon, Hughes, Westinghouse and other industries sponsored by DOD. MSFC and now JSC are managing small phase commanded array work at TI for the shuttle.

The largest, highest CW powered phased array near S-band is a command steered unit at Elgin AFB, Florida.

- Capabilities and Experience

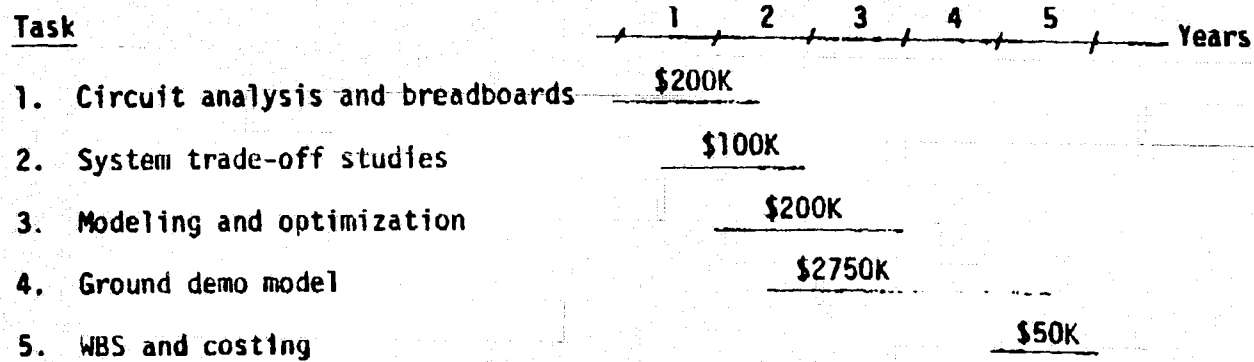
JPL has long and extensive experience in analyzing and designing phase locked loop control systems and high isolation, closely spaced in frequency coherent spacecraft transponders and high power transmitter-low noise receiver combinations--the type of technology deemed to be applicable to solving the phase reference distribution and retrodirective phased array problems over a kilometer diameter sized structure.

Other NASA centers and some industries such as Motorola, Philco, Hughes and RCA possess certain capabilities in these technology areas also.

TRANSMISSION PHASE CONTROL (D. 2)

Preliminary Program Estimates

Cost and Schedule



● Present Efforts

JPL is currently analyzing and breadboarding a version of a retrodirective and phase reference distributing phase locked loop array model.

Planning for a modular power transmitting phased array to be used in a FY '78 demonstration at Goldstone with the existing 24m^2 area rectenna array is underway.

D.3 WAVEGUIDE

Background

The power satellite microwave beam radiating antenna structure must provide for integrating and supporting the DC to RF converter devices in order to minimize path length losses while distributing the power signals and then radiating virtually all of the power with a locally uniform power density. The radiating structure is currently proposed to be an array of slotted waveguides.

Spatially, the waveguide radiators must provide for maximum power density in the center of the array and minimum density in the elements near the edge. The degree of resulting amplitude taper and the allowable quantization approximation error are functions of the system sidelobe level-beam efficiency, RFI and biological requirements.

The varying power density between array elements can be accomplished by simultaneously varying the density of DC to RF converters per unit of area and the waveguide slot coupling design.

Depending upon the DC to RF converter gain characteristics and the phase control system mechanization, the slotted radiator waveguide sections may be either series or parallel fed from the converters. Design tradeoffs exist concerning noise adding, redundancy, simplicity and weight.

The maximum single waveguide array element size is determined by the allowable electronic beam steering angle loss in the system design and the allowable increase in differential phase error between points in the element aperture due to aging or environmental changes.

Ideally, the waveguide should provide a surface along which monitoring and control instrumentation cables and DC power distribution lines, high voltage shielding, phase reference distribution transmission lines and circuitry can be supported.

The material should have low outgassing, low differential thermal coefficient of expansion to maintain phase velocity, high RF conductivity for low RF loss, low thermal impedance and high emissivity to assist in the converter device

waste heat removal, smooth surfaces to yield low RF loss, low RFI, and to provide a high RF breakdown margin.

Also, the guide should be capable of space manufacturing and assembly to extremely tight tolerances. The structure must accommodate attachment points for installation and leveling adjustment, signal sample points, filtering, diplexing and potentially flexible input/output connections for stress buildup relief or assembly tolerances.

A low sunlight reflectance surface finish is desirable to prevent interference to satellites optical reference systems and optical astronomy.

The guide must assist in providing the proper impedance load for the DC to RF converters and the structural--RF layout must lend itself to being juxtapositioned in order to maintain the radiator surface pattern replication.

The structure must be lightweight yet it must provide sufficient stiffness against which the forces attendant to the maintenance operations of changing tubes and/or cathodes can be adequately resisted.

Criticality

The RF waveguide structure is critical to the satellite power system because its RF loss and phase stability directly affect the power transmission efficiency which affects the solar collector size.

Although new composite materials with special surface treatments have been suggested for potential use, a sample radiator element has yet to be fabricated and tested. Thus, it is difficult to accurately predict the required tolerances, materials, and cost of fabricating at this time. The operating environment and conditions need to be defined in better detail to assist in setting design and performance requirements. Thirty year lifetime wearout and maintenance requirements need to be identified. The time to phase stabilize after eclipse needs to be calculated because it would affect the allowable system operating fraction.

Objectives of Required Efforts

1. Determine the detailed waveguide operating environment and interfaces: thermal inputs and outputs/RF current densities/guide and slot voltages/mounting forces/attitude adjustment points/converter mounting flanges/signal sample points/number and type of element input and output points/atmosphere-ionosphere/ultraviolet radiation intensity.
2. Perform system tradeoff and determine performance requirements: goal of contribution to beam efficiency/select mechanical and electrical configuration series or parallel feed/select material requirements/set fabrication and assembly tolerance goals/method of tiling the plane.
3. Investigate space fabrication, surface finish, assembly, test and maintenance techniques. Perform material developments/joining techniques.
4. Measure: beam efficiency and phase stability/aging characteristics/power handling breakdown margins/RFI generated/filtering characteristics/signal sampling accuracy/outgassing/thermal-vacuum eclipse phase recovery time.
5. Project cost and performance.

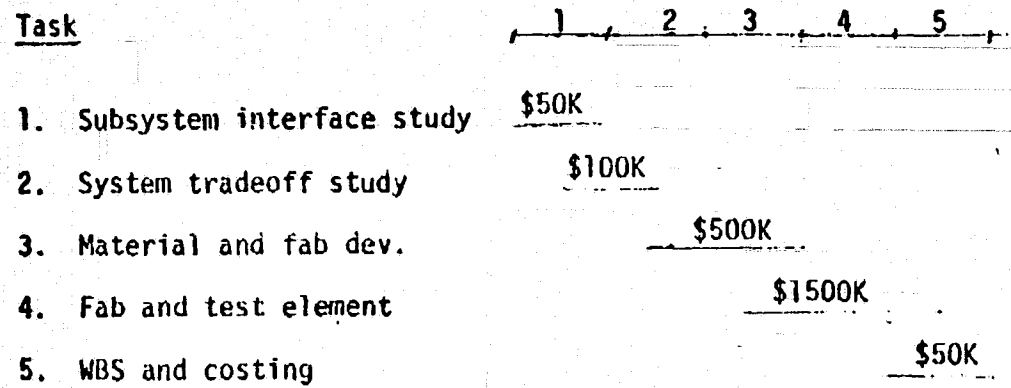
Recommended Approach

1. Perform design exercises with DC-RF converter, phase control and backup support structure subsystems to identify tradeoffs and to determine interfaces and tolerances.
2. Participate in overall system optimization tradeoff studies and set waveguide requirements.
3. Write specifications and objectives for and let contracts for material development and testing, fabrication and maintenance study.
4. Contract for fabrication and ground and space testing of a representative radiator element.
5. Develop detailed work breakdown structure and estimate resources.

Preliminary Program Estimates

- Cost and Schedule (see chart)

WAVEGUIDE (D. 3)
Preliminary Program Estimates
 Cost and Schedule



- Available Technology

Slotted waveguide array analysis techniques, designs and hardware exist. However, they are optimized for other applications. The high operating temperatures, very low phase error requirements and 30 year space life-times and space assembly tolerances require new materials to be constructed and tested.

LeRC has in-house composite analysis, design, fabrication and testing capabilities. General Dynamics, Hughes, Lockheed and Philco have built and tested microwave composites for DOD and NASA; filters and reflector antennas.

- Capabilities and Experience

S-band slotted waveguide array designs were used on the Surveyor high gain antenna built by Hughes for JPL. Westinghouse, RCA and Raytheon also possess capabilities for design and fabrication although most of the slotted guide work has been done at X-band.

- Present Efforts

None directly applicable to the material and RF designs in the high temperature space environment and at S-band.

The JSC space assembly contract at Martin is applicable to the waveguide element assembly into the total radiator.

D.4 RF-DC CONVERSION

Background

The earthbound end of the satellite power link must perform not only the function of converting the microwave energy to a more useful form, but must first efficiently collect the RF energy. This is accomplished by allowing little or no reflected energy at either the carrier frequency or harmonics and a large area collector. The conversion function must occur most efficiently over a range of input power levels and output load variations.

The collection area must be large enough to embrace a large percentage of the incoming beam even in case of design allowable beam wander, yet the diameter must be restricted so as to minimize the total area required for the collector. The tradeoff determining collector size and shape will be different depending upon collector location and whether or not it is to be served by multiple satellites. Additionally, a guard ring will most probably be required around the collector area for biological warning and restriction.

A design tradeoff exists with regard to maximizing the conversion efficiency by grading or tailoring the nominal operating power level of the converters to allow matching of their highest efficiency operating point to the available power density. The obvious danger in this scheme however is that a larger than anticipated beam movement possibly coupled with a load decrease may result in overstress to those units working at the normally low power density.

If the probability of overstress is low and the cost of replacement is also low, a strategy of replacement upon overstress may be satisfactory.

Otherwise, protective devices may have to be incorporated into the collector-converters. The increased loss and cost must be further traded off against the simplicity of a single device design operating with less efficiency at the edges where the power density is less.

Additional system trades exist in the area of an overvoltage, crowbar, load maintaining or managing device that may be required to limit the internal dissipation increase in the converter when it is not properly terminated.

If there is significantly correlated reflected power from an other than optimally terminated collector-converter, the reflection may cause undesirable reactions at the DC to RF converters at the spacecraft. The collector could be designed to return reflected signals to directions other than the transmitter, but this may compromise collection efficiency.

Thus, tightly maintained management of the converter output power conditioning may be required for system stability.

It is desirable to have the collection function possess an all weather capability. At S-band, crystalline and vapor forms of precipitation will not cause significant attenuation. However, depending upon the form of collector and converter, the liquid form of precipitation may cause significant attenuation via de-tuning exposed tuned circuits.

All collectors will be subject to tornado, hailstone and lightning damage in varying degrees. Also, leaves, trash, tumbleweeds, dust, bird droppings, etc. will require maintenance cleanup.

The pilot(s) transmitters and antennas must be integrated within the collector area along with performance monitoring, power collecting and processing, and control systems.

Additionally, in some cases it may be desirable to attempt dual use of the collector area by, for example, designing the collector-converter to be partially transparent at optical frequencies.

The present collector-converter concept of the "rectenna" element using dipoles and diodes results in a rather low voltage DC output that will require large collection conductors or many local power conditioners in order to keep DC output collection losses small. Nevertheless, the rectenna concept possesses the desirable features of being relatively insensitive to pointing angles, highly efficient, low RFI generator, requires a small mass of materials and is susceptible of being mass produced.

The coupling between adjacent elements should be designed to yield near 100% RF absorption under normal conditions while minimizing the number of

elements per unit of collector area and if an element should fail the overstressing of adjacent elements should be minimized.

The polarization of the elements represents a tradeoff between the mass of material in the collectors and operational performance requirements to serve several satellites or due to propagation de-polarization conditions.

The optimum edge location and termination scheme needs to be investigated.

Criticality

The RF to DC collection and conversion function is critical to the satellite power system because it is in series with the chain of energy transmission from sunlight to buss bar output. Consequently, its efficiency performance thus affects the solar collector size for a given level power system design.

Again similar to the DC to RF conversion function, the "electropolitical" acceptance of the system will depend in part upon how well any spurious and harmonic or undesired fundamental radiation can be managed to accommodate particular national or international operational agreements. Tradeoffs between RFI levels and filter insertion loss at the fundamental along with reflection control by load management will be necessary.

The state of technology concerning the collection-conversion function is in reasonably good shape at least compared to other areas of the system. However, questions of lifetime, mass manufacturing techniques and installation costs, optimum tradeoffs between the converter output and the output power conditioning, and unequal load sharing between rectenna elements must still be answered or resolved.

Objectives of Required Efforts

1. Determine detailed subsystem operational interfaces and environment range: design wind load/seismic protection/temperature range/precipitation/DC output collection scheme/monitoring instrumentation for voltage, current, temperature and incident flux density/pilot(s) antenna(s)/ground stand-offs/maintenance access and locomotion/guard ring interior perimeter/crowbar/waste heat removal method.

2. Determine system and subsystem performance requirements: identify and resolve requirements to operate at intermediate power levels, with modulated waveforms, under continuous all weather conditions, or with dual function ground utilization/efficiency goal/cost goal/RFI levels/multiple pilots/capability to accept inputs from multiple satellite positions/degree of transmitter array protection from reflected power/tolerance to beam wander overstress/requirements for visual aesthetics/allowable RF leakage/lightning protection.
3. Increase rectenna diode efficiency at low power levels and increase production yields, simplify package to plastic encapsulated beam lead and life test.
4. Simplify rectenna configuration, mass manufacturability, increase collection-conversion efficiency, and resolve unequal load sharing in array.
5. Determine impacts and tradeoffs between converter and output power conditioning.
6. Project cost and performance.

Recommended Approach

1. Perform design exercises with DC power collection and load management subsystems in order to determine interfaces and identify tradeoffs and tolerances.
2. Participate in overall system optimization tradeoff studies and set RF to DC collector and converter requirements.
3. Advanced rectenna development contract.
4. Continue large scale, high power rectenna performance tests at Goldstone. Develop and test load managing schemes and equipment. Interface with modular power phased array and control system to determine system stability.
5. Develop detailed work breakdown structure and estimate resources.

Preliminary Program Estimates

- Cost and Schedule (see chart)

RF-DC CONVERSION (D. 4)
Preliminary Program Estimates
 Cost and Schedule

<u>Task</u>	<u>1</u> / <u>2</u> / <u>3</u> / <u>4</u> / <u>5</u> / <u>Years</u>
1. Subsystem interface study	<u>\$50K</u>
2. System tradeoff study	<u>\$75K</u>
3. Advanced rectenna contract	<u>\$2000K</u>
4. Rectenna test and load management	<u>\$175K</u>
5. Ground systems testing	<u>\$250K</u>
6. WBS and costing	<u>\$50K</u>

- Available Technology

A 24m² area high power rectenna array by Raytheon for JPL has demonstrated 30.2 KW of DC output with 82.5% collection-conversion efficiency for approximately a 3 dB intensity taper maximum over the array. Integrated beam power RF to DC efficiency if fixed tuned elements filled circular symmetric beam calculates to be approximately 70%.

One hundred ninety-nine GaAs rectenna elements with a Gaussian range of RF powers from approximately 9W to 0.1W have just passed (6-75) 2000 hours of accumulated life test time.

Computer programs to calculate array element performance under various illumination conditions exist at JPL. Monopulse type beam center location via array element output voltage or power calculations are quite accurate-- could provide beam location pointing information.

End to end DC to DC efficiency measurements of a complete microwave power transmission scheme at Raytheon using a dual mode horn radiator and an approximately circular outline rectenna array have been documented in JPL TR 33-727.

- Capabilities and Experience

Both LeRC and JPL have capabilities to manage rectenna development and test contracts.

JPL has high power microwave test range at Goldstone.

Raytheon is current outstanding leader in the field of rectennas.

- Present Efforts

Negotiations are underway between LeRC and Raytheon for an advanced high efficiency at low RF power density rectenna element.

Evaluation tests are continuing of the high power rectenna array at Goldstone by JPL.

Planning for the modular power transmitting phased array to complete a ground test system is underway at JPL.

D. 5 MICROWAVE BEAM PROPAGATION TECHNICAL CONSIDERATIONS

Background

The RF beam of the satellite power system which is formed by the phase control system and radiated from the slotted waveguide array provides the essentially massless link between spaceborne transmitter and earthbound receiver. The RF beam ideally provides nearly lossless energy transport while propagating from the subarray elements through the following:

1. Any local atmosphere-ionosphere near the large space structure due to outgassing, photo, field or charged particle induced emission.
2. Any intervening dielectric or metallic support structure as proposed in some schemes to separate halves of the solar collectors.
3. The intervening solar wind in space.
4. The Earth's magnetosphere, ionosphere and atmosphere.
5. The local microclimate due to waste heat liberation and albedo modification of the collector-converter.
6. Any intentional or unintentional radome on the collector such as water film, radial ice, snow, dust, birds, trash, weeds, leaves, etc.

However, in the above propagation path elements losses can occur due to scattering, absorption, beam displacement and depolarization.

Scattering losses arise from adjacent or intervening dielectric or conducting structures. Such losses can be minimized by careful structure design except for trash on the RF collector, wet hail, leaves, tumbleweeds, etc.

Absorption occurs due to certain inelastic molecular vibrations induced by the changing electromagnetic fields as in microwave heating of foods and loss in wet hail or melting snow. Absorption losses also occur in the Earth's atmosphere due to oxygen and water vapor, but they are quite small at S-band.

Beam displacement comes about from the RF energy traversing a region of changed dielectric constant such as the Earth's ionosphere or a sharp weather front. Again, at S-band the effect is quite small. The transmitted beam could also be displaced by action of rapid, massive charged particle movement or density changes affecting the pilot signal phase front. At S-band and for regions

displaced from the Earth's magnetic equator, the probability of occurrence and the magnitude are thought to be small.

Depolarization occurs when the RF beam traverses a region of charged particles in a magnetic field. For a linear polarized signal at S-band and received at temperate latitudes, the result may be up to 12 deg. of rotation of the signal polarization. Although normally small, it may not be negligible in the system design. The effect could be compensated by, for example, rotating the transmitting antenna about the beam propagation axis or circularly polarizing the receiving collector.

Ionospheric propagation effects are a function of solar activity and electric field strength and thus high power densities must be investigated thoroughly to better quantize long term effects.

High power flux density can induce changes in the ionosphere. At very high levels this could lead to significant attenuation. At lower levels it could enhance long distance HF communications which in some cases would contribute to RFI.

General non-linear processes in any of the propagation path elements can contribute RFI.

General non-linear processes in any of the propagation path elements can contribute RFI.

Criticality

The losses and variations in the propagation path from transmitter to receiver can affect the system power transmission efficiency, safety and stability. These results in turn affect the solar collector size, RF collector, guard ring and the source and load management control system design and performance. Significant long term, high power density, S-band ionosphere propagation data as affecting large aperture antennas on both ends of a communication link is lacking.

The phase accuracy performance of the pilot controlled retrodirective array as a function of beam flux density and solar effects will need to be calculated and measured.

RFI affects in conjunction with various beam flux densities and solar eruptions will need to be quantized--both self generated and externally enhanced.

Depolarization compensation strategies may need to be devised.

Objectives of Required Efforts

1. Quantify the propagation path elements; near the large space structure/ between satellite and Earth's ionosphere/Earth's ionosphere/Earth's atmosphere/near the Earthboard RF collector.
2. Determine the magnitude of propagation effects on: pilot phase front/power beam phase front/power beam attenuation/polarization/RFI generation/ RFI enhancement.
3. Develop applicable system or subsystem reactions to propagation effects: depolarization compensation/propagation attenuation source compensation or load following/collector maintenance.

Recommended Approach

1. Preliminary design study with adjacent RF transmitting and RF collecting subsystems in order to identify propagation interfaces. Also with meteorologists and atmosphere-ionosphere experts to define propagation environments.
2. Perform detailed analysis and calculations of propagation effects. Conduct measurements and experiments. Determine flux density limitations.
3. Participate in overall system optimization tradeoff study to set performance capabilities.
4. Develop WBS for remaining long term efforts.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Available Technology

Some parts of the analysis and operating experience of synchronous orbit communication satellites, spacecraft charged particle experiments, deep space communications, re-entry plasma and launch breakdown experiments, HF ionosphere modification experiments.

MICROWAVE BEAM PROPAGATION - TECHNICAL CONSIDERATIONS (B. 5)

Preliminary Program Estimates

Cost and Schedule

<u>Task</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>Years</u>
1. Preliminary design study	<u>\$500K</u>					
2. Analysis, experiments		<u>\$1250K</u>				
3. System optimization				<u>\$75K</u>		
4. WBS and costing					<u>\$50K</u>	

- Capabilities and Experience

NASA centers and universities planetary ionosphere and atmosphere scientists, Stanford, MIT, Texas, Comsat propagation analysis, industry experts, Hughes, Lockheed, Raytheon.

- Present Efforts

None known other than Raytheon Co.

D.6 RADIO FREQUENCY INTERFERENCE

Background

A satellite power system must operate in the context of a utility of the Earth. Hence the SPS must co-exist with other national and international RF spectrum users such as DOD Comsats, intelsats and earthbound communication services as well as the listen-only and radar and optical astronomers, in addition to deep space and manned probes, Earth sensing, broadcasting and relay satellites of NASA.

In addition to the multi-gigawatt power carrier and lower level harmonic and spurious radiation from the sky and Earth ends of the system, the SPS will require pilot, command, monitoring and control links from spacecraft to Earth and maintenance links on the spacecraft. Thus significant portions of the already crowded RF spectrum are affected by an SPS.

The sheer magnitudes of the RF power level and harmonics may necessitate the abandonment of certain small portions of the RF spectrum by certain users.

Negotiations will be inevitable with existing and potential national and international spectrum users. Accommodations regarding the S-band center frequency and guard bands about the carrier, harmonics and spurious levels will be required.

Detailed data concerning projected RF performance capabilities and requirements must be generated by measurement and calculations.

Criticality

The required RFI performance of the SPS directly affects the system power transfer efficiency through the filtering loss encountered by the power carrier signal. Filters are necessary to reduce out of band signals to predetermined levels. The predetermined levels are national regulations or international agreements to which the U.S. subscribes.

The center frequency at which the SPS will operate determines the amount of atmospheric attenuation and thus the assigned frequency is critical to the power transfer efficiency.

The currently proposed S-band 2450 MHz carrier in the U.S. ISM (industrial, scientific and medical) band is not an international band under ITU (International Telecommunications Union) definitions. In fact, although RF power transmission is allowed under U.S. O. T. P. (Office of Telecommunications Policy) or FCC (Federal Communications Commission) regulations, there is no definition of a satellite power service in the ITU regulations.

The optical and infrared reflections and emissions from such a large, hot device must also be given due consideration in terms of electromagnetic interference, satisfying the consequences of which may affect the system performance.

RFI regulations will require DC source and load switching shielding and filtering which will affect system efficiency.

Objectives of Required Efforts

1. Determine spectra and performance of each potential DC-RF converter when coupled to candidate radiating antenna elements.
2. Research FCC and ITU regulations to ascertain requirements.
3. Perform system tradeoff studies to determine impacts on SPS and other spectrum users, options for a clear or shared channel.
4. Obtain national-international accommodation regarding S-band center frequency, guard band about carrier and harmonic and spurious levels.

Recommended Approach

1. Perform RFI spectrum measurements on existing similar DC-RF devices such as amplitrons and klystrons when married to S-band slotted waveguide arrays. Develop measurement techniques, make projections of results and plan for the measurement program on candidate converters as they are developed.
2. Let study contract to perform regulation research, determine impacts on other spectrum users and to make recommendations.
3. Participate in overall system optimization tradeoff studies.
4. Prepare for an FCC notice of inquiry. Consult with OTP and IRAC (Interagency Radio Advisory Committee).

Determine options, conditions of usage, frequency sharing criteria and related

data with a view toward generating the U.S. State Department official position paper. Prepare data for an ITU WARC (World Administrative Radio Congress) resolution to recommend a CCIR (International Radio Consultive Committee) study of power satellite service for a future WARC consideration. Obtain a definition of satellite power service, band allocation, and eventual frequency authorization.

Preliminary Program Estimates

● Cost and Schedule (see chart)

● Available Technology

Slotted S-band waveguide and klystrons available, amplitrans could be simulated by magnetrons to get started on RFI typical measurements. Analytical RFI prediction techniques have large uncertainty.

● Capabilities and Experience

Most NASA centers have RFI groups. NASA HQ OTDA is U.S. CCIR Representative. JPL has a communications spectrum management group headed by Sam Brunstein who, along with Sam Fordyce, was a delegate to the 1971 CCIR meeting.

● Present Efforts

No known formal efforts in progress.

RADIO FREQUENCY INTERFERENCE (D. 6)

Preliminary Program Estimates

Cost and Schedule

<u>Task</u>	<u>1</u> <u>2</u> <u>3</u> <u>4</u> <u>5</u> <u>Years</u>
1. Spectrum measurements	<u>\$300K</u>
2. Study contract	<u>\$300K</u>
3. System tradeoff study	<u>\$75K</u>
4. Accommodation work	<u>\$ 500K</u>

E. ENVIRONMENT/ECOLOGY

E.1. BIOLOGICAL EFFECTS OF MICROWAVE BEAM

Background

All presently proposed methods for the production of power in space have in common the transport of very large amounts of energy by microwave from space to Earth. The environmental impact from this transmission received over many square miles appears to be far less than other solutions to the energy problem but many aspects have not been researched in depth nor has the technology been field tested. The most prominent of these areas requiring additional knowledge before the environmental impact can be assessed is the Biological/Ecological effects of microwave irradiation over very large areas where flora and fauna are subjected to continuous exposures throughout their life-cycles for many generations.

In the United States the limitation for acceptable, continuous exposure to microwaves has been set at 10^{-2} w/cm²; comparable standards within the USSR are set at 10^{-5} w/cm². Considerable controversy exists about the validity of the criteria used in Russia to limit exposures to such low doses. In the United States the acceptable field strength is based on the level at which no build-up in tissue temperature occurs since it is believed that microwave damage to biological tissues is caused by a temperature effect. If the organism involved can remove the heat at a sufficient rate to prevent an increase in temperature the field flux is considered to be acceptable. The Russians on the other hand believe that there are non-thermal biological effects produced, particularly those associated with the nervous system. It is their belief that impulses can be produced within nervous tissue through increased molecular activity and that these effects can be observed as behaviorial changes.

During the last 20 years eastern European scientists have built a body of microwave literature that has resulted in concern about a possible health hazard related to long-term, low-level exposures to microwaves. In the United States the acceptable dose of 10 mw/cm² has no factor included in it for the accumulation

of any effects with time. In the Soviet Union microwave safety standards are up to one thousand times stricter than those of the U.S. "Microwave Sickness" is a recognized occupational disease which includes symptoms ranging from increased irritability to cardiovascular effects.

Most of the studies upon which U.S. acceptable dose standards are based originated in the Department of Defense. The Defense Department set up a tri-service group to study the matter in 1956 and four years later recommended the standard of 10 mw/cm^2 . That conclusion was reaffirmed in 1973 by the American National Standards Institute, however, it should be pointed out that the tri-service group fixed the standard on the basis of experiments mainly involving levels in excess of 100 mw/cm^2 . The "thermal threshold" is generally taken as 100 mw/cm^2 (above which living tissue begins to accumulate heat). Below 10 mw/cm^2 the controversy exists, and the Environmental Protection Agency has been quoted as saying the data base is inadequate; however, the limit remains at 10 because nothing indicates that there is a frank hazard.

The World Health Organization has recently been concerned with the problem during investigations of the North Karelia Project, a study of three small towns in Finland directly in the path of an "over the horizon" radar that sets up a field following the curvature of the Earth. Karelia is a rural area of Finland inhabited by farmers and lumberjacks. Unexplained incidents of heart attacks among young and old alike reached epidemic proportions several years ago causing the population to petition the Government to do something. A statistical study was launched under the auspices of the World Health Organization in 1973 and a report on the project indicates that in the area of North Karelia the incidence of heart attack is extremely high. A neighboring town has one of the highest known rates in the world. The World Health Organization is now being encouraged to expand the scope of the study to investigate the microwave factor in other areas, since it has been claimed

that cancer also appears to be unusually high in small villages subject to prolonged microwave emissions that would be considered acceptable by U.S. standards.

Criticality

Detailed design of the microwave power transmission system will require information about environmental effects of microwaves that is not presently available. There is considerable lack of understanding concerning the effects of microwave radiation on living organisms and how to measure the absorbed dose. Although there are some data available on the effects of acute exposures of man and some animal, there is insufficient data on chronic exposures to animals or to large land areas, particularly plants or soil.

Indirect effects must also be considered in design of an environmentally acceptable system. Such factors include heating of the atmosphere and ionosphere (see E.3.). Indirect atmospheric effects could impact the terrestrial flora and ocean plankton through a change in atmospheric ultraviolet filtration. Prior to any commitment to an operational program we must have evidence that all ecological impacts have been studied and that plans are based on a firm understanding of the situation. Unfortunately, progress on biological, microwave research has been very slow, yet information is required as soon as possible in order to complement and supplement the engineering development.

Objectives of Required Efforts

1. Determine the effects of a continuous, lifetime exposure to various microwave energy density levels to a wide variety of flora and fauna. This should include humans, farm animals, birds, insects, soil microorganisms, trees, and plants.
2. Determine any biological effects due to modification of the ionosphere and/or atmosphere by a microwave beam (related to E.3.).
3. Set and empirically test limits of exposure to microwaves both inside and outside of any "restricted area" set up around the ground station.
4. Develop required dosimetry to measure absorbed doses as a function of density and time.

Recommended Approach

1. Preliminary Research Requirements Study

A study effort is required to ascertain the applicability of existing efforts, and to familiarize those programs with the goals of the SPS program. State and federal agencies associated with agriculture and farm products also need to be informed about the question of space power system impacts. Some NASA efforts currently underway may also be re-oriented toward the study of ecological effects produced by microwaves.

With minimal funding it should be possible to acquire the assistance of many research workers to use the Goldstone facility to do preliminary studies on all phases on the ecological problem. The general approach would be to coordinate these interests with the ongoing studies being conducted by JPL and LeRC to the greatest extent possible. It is anticipated that such studies may be conducted for two or three years until more sophisticated facilities are available.

Additional, detailed study and test requirements of followon efforts would be determined in this preliminary study.

2. Study of Prolonged Microwave Exposure of Livestock and Birds

This study should determine permissible continuous exposure levels of microwaves for poultry and other livestock. Studies should be made to determine the effect of continuous exposure to microwaves on the development of birds for food and egg production and for the production of livestock under laboratory conditions. Effects of local heating on birds, small animals and insects would be included.

3. Study of Microwave Effects on Soil Microorganisms

This study should determine the effects of the microwaves on microorganisms and the changes produced in the soil for representative areas in the United States. Studies should be done with samples of soil and native organisms using the range of microwave densities foreseen for orbit to Earth

transmission. Such studies should be done first in the laboratory and then, possibly, in large-scale simulated field conditions.

4. Study of Microwave Radiation on Plant Growth

Determine the effects of microwaves on the plant life to be found in typical ground station areas. Include both natural and cultivated plants.

5. Test-Facility Requirements Definition

Define the requirements for and perform conceptual design of a research facility for ecological impact studies if earlier studies indicate the need.

6. Work with other agencies to apply early study and test results to the setting of close limits.

7. Dosimetry Development for Continuous Microwave Exposure

Develop a means to survey the large areas of ground stations to establish the intensity distribution and to monitor the accrued dose of microwave energy. Both in situ and remote sensing will probably be employed.

8. Study to determine biological effects of atmospheric/ionospheric modification.

Define alterations, if any, in UV penetration and determine any resultant changes in ecological areas.

Preliminary Program Estimates

① Cost and Schedule (see chart)

② Related Efforts

- A large number of laboratories are currently working in the area. Different forms of tissue consist of different densities and dielectric properties and dose absorption varies greatly from point to point within the body. At present there is no quick way to evaluate the effect of an absorbed dose. Almost all of the present studies underway are oriented toward establishing a safe exposure level for man and to develop a means of monitoring an absorbed dose in a way that it has significance for the prognosis of effects.
- Safety studies and efforts pertaining to microwave ovens.

BIOLOGICAL EFFECTS OF MICROWAVE BEAM (E. 1)

Preliminary Program Estimates

Cost and Schedule

TASK	FY	1	2	3	4	5
1. Preliminary Study		\$100K	\$100K	\$100K		
2. Microwave Exposure of Livestock and Birds			100K	150K	\$150K	\$150K
3. Microwave Effects on Soil Microorganisms			50K	50K	75K	75K
4. Microwave Radiation on Plant Growth			100K	100K	60K	60K
5. Test-Facility Definition			30K	100K	1,000K	2,000K
6. Dose Limits (Interagency)		50K	50K	100K	100K	100K
7. Dosimetry Development			50K	50K	60K	60K
8. Biological Effects of Atmospheric/Ionospheric Modification			50K	50K	60K	60K

E.2. TRANSPORTATION SYSTEM POLLUTANTS

Background

The upper atmosphere is the most critical part of the atmosphere from the pollutant point-of-view because its natural "cleansing" action is very slow. Any pollutants that eventually result in a decrease in the ozone density must be thoroughly understood or eliminated from consideration.

Considerable evidence has appeared recently concerning the stratospheric pollution by chemicals capable of reducing the Earth's ozone shield. Much of the information has centered around the oxides of nitrogen (NO_x) that are released from high altitude jet aircraft. The oxides of nitrogen which are of concern to this program are formed by the high temperatures existing in the plumes of the rocket boosters. The amount of NO_x is dependent upon plume shape and it is possible that this could be reduced by using variable expansion ratio engines. These oxides of nitrogen, when produced in the area of the ozonosphere, react directly with the ozone and can reduce the content significantly.

Another means of producing oxides of nitrogen is by the surface heating that takes place upon reentry of objects returning to Earth through the rarified atmosphere. It has been calculated that the NO_x production could be as high as 10 to 15 percent of the weight of the reentering vehicle.

Much attention has also been given to the free chlorine that is derived from the chlorofluoromethanes (freon) that are used in spray can propellants, refrigerants and as a cleaning agent in many industries. Carbontetrachloride and methylchloride are also present in the atmosphere and may be contributing free chlorine to the stratosphere. Present indications are that free chlorine is of principal concern, but the full seriousness of its actual ecological threat has not been fully established.

The compounds are extremely stable and are only decomposed at very high altitude by high intensities of ultraviolet radiation, around 30 kilometers. Current studies using models of photochemistry and transport processes in

the stratosphere show that the halomethanes already present in the atmosphere are sufficient to make significant decreases in the ozone layer; however, the most current research tends to show figures that have been revised downwards from those previously published. Although results are not consistent from laboratory to laboratory they do appear to agree that the halomethanes in the atmosphere have already reduced ozone concentrations by about 0.5 percent. If the halomethane production were halted completely around the world, the ozone depletion would climb from about .7 percent in 1978 to a maximum of about 1.7 percent in 1990 before leveling off.

It is thought by many that the life processes on Earth are significantly influenced by the amount and spectrum of the UV light that penetrates through the ozone shield. Predictions are made that incidence of skin cancer would be increased following an increase in UV. Other matters of concern are the effect that UV has on the plant life. Of perhaps even greater concern is the effect that such a change would have on the ocean plankton. The plankton that is produced on the surface of the oceans is the beginning of the food cycle for all the fish and aquatic animals, which in turn supports much of the life as it exists on Earth.

Criticality

One of the principal pollutants in the discharge of the space shuttle solid rocket booster motor is HCl. This is produced by the solid propellants and is deposited mainly in the troposphere where it is removed quite rapidly. However, large quantities are deposited in the stratosphere. The hydrogen does not itself cause adverse environmental effects at high altitude, but free chlorine produced by HCl disassociation destroys ozone through catalytic reactions with odd oxygen ($\text{CH}_3\text{O} \rightarrow \text{ClO} + \text{O}_2$, $\text{ClO} + \text{O} \rightarrow \text{Cl} + \text{O}_2$) these processes are analogous to the catalytic destruction of ozone by odd nitrogen compounds (NO and NO_2). The oxides of nitrogen are produced by high temperatures within the turbulence of jet powered aircraft and are also produced by the plume of the rocket.

Satellite power systems require vast amounts of material to be put into orbit, some estimates exceeding one hundred million pounds. The use of a solid propellant which releases chlorine compounds in any form would probably be unacceptable. For the anticipated traffic model the solid propellant used in the first stage of the space shuttle would probably be sufficient to reduce the ozonosphere measurably. (It must be remembered that the supersonic transport program was discontinued largely on the basis that it might cause a 10 percent ozone reduction.)

The extent to which a kerosene system would be a pollutant problem has not been studied extensively, but it is generally agreed to be significantly less a problem than solid boosters.

The transfer vehicle used to move the structure from low Earth orbit to geosynchronous orbit is another potential polluter. The solar electric propulsion system (proposed by many as the transfer vehicle) ionizes a heavy metal (e.g. mercury), accelerates it, and expels it to derive a reaction thrust. Preliminary analyses indicate no problem, but they are incomplete and were not performed on a traffic model as large as would be involved for satellite power systems.

Another pollution factor is that in the construction of satellite power systems very large amounts of orbital litter could accrue. Hopefully design will be able to incorporate most of what is taken into space into some part of the structure. However, many tanks, pallets, etc. will be required that probably will not be economically feasible to return to Earth.

Such garbage can certainly be considered a pollutant factor.

Objectives of Required Efforts

1. Determine all emissions of stages and boosters considered for satellite power system usage.
2. Using the appropriate traffic model determine the impacts of these emissions:

- HCl in upper atmosphere
 - Heavy ion injection into magnetosphere
 - Interruption of ionospheric F2 layer by launch
 - NOX production in D layer by re-entry and skip braking
 - RP-1 products and NOX produced by plume
 - H, OH and H₂O in upper atmosphere
 - Others
3. Study and classify short, intermediate, and long term effects
 4. Identify secondary impacts to be considered in other areas
 5. Provide data necessary for trade-offs to minimize impacts
 6. Define program to manage space "garbage"

Recommended Approach

1. Make sure efforts in all other areas provide the necessary pollution data to avoid costly duplicate efforts.
2. As part of the studies for the HLLV and the transfer vehicle determine the emissions from all candidate vehicles.
3. Pollution study to determine the impacts of the emissions of all candidate transportation system vehicles and to provide data for use in system studies and trade-offs.
4. Study to define program to manage space "garbage" (to be part of Large Space Structures efforts).
5. Improve atmospheric modeling to the point necessary to support the above efforts.
6. Plan the necessary ground and space based experimentation.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Applicable Efforts
 - JSC is currently studying the shuttle impact on the environment. A group is devoted specifically for this and perform atmospheric sampling with aircraft and balloons.

TRANSPORTATION SYSTEM POLLUTANTS (E. 2.)

Preliminary Program Estimates

Cost and Schedule

TASK	FY	1	2	3	4	5
Studies to Determine Emission Impacts		250K	250K	450K	450K	200K
Atmospheric Modeling		500K	500K	500K	500K	500K
Experiment Definition and Planning		250K	250K	300K	300K	500K

- ARC has an extensive computer modeling program for upper atmospheric dynamics, presently progressing from 2D to 3D model.
- JPL is doing atmospheric sampling at all levels to determine chemical kinetics.
- LeRC is also doing related atmospheric work.
- GSFC is involved with atmospheric remote sensing at all levels.
- LaRC is concerned with atmospheric pollution and processes.

E.3. MICROWAVE BEAM PROPAGATION - ENVIRONMENTAL CONCERNS

Background

See D. 5.

Criticality

As mentioned in E. 1. any significant decrease in the atmospheric absorption of UV would be a major problem area. In addition the secondary effects from heating of the atmosphere and ionosphere are largely unknown, as is the question of the formation of any new products.

Objectives of Required Efforts

1. Working within the efforts mounted to resolve D. 5. identify potential environmental impact areas for further study. Perform the indicated followon studies.
2. Determine any limitations on the microwave power transmission system due to environmental concerns of beam/atmosphere interactions.

Recommended Approach

1. Work within effort for D. 5.
2. Necessary followon studies to assess environmental impact and to provide tradeoff data.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Capabilities and Experience
 - JPL and LeRC are working in related areas.

MICROWAVE BEAM PROPAGATION - ENVIRONMENTAL CONSIDERATIONS (E. 3.)

Preliminary Program Estimates

Cost and Schedule

TASK	FY	1	2	3	4	5
Technical Considerations Efforts		←————→				
Followon Studies			← As Required 50K	50K	100K	100K

APPENDIX 1 - POWER RELAY SATELLITES FOR TRANSMISSION OF POWER

Background

The Power Relay Satellite (PRS) has been proposed by Ehricke ("The Power Relay Satellite" parts I and II, Rockwell International E74-3-1 and E74-6-1) as a means of transmitting power from one point on the Earth to another. As described in the "Preliminary Technology Assessment" the system has many characteristics common with the Satellite Power Systems.

The Power Relay Satellite System encompasses the Transmitting Antenna System (to convert the generator output to microwaves and transmit a microwave beam to the relay), the Power Relay Satellite in GSO (to passively reflect the microwave beam toward the ground reception site), and the Electromagnetic Power Plant (exactly equivalent to the RF-DC converter and utility interface of the SPS). The Relay System is entirely a transmission system, generating no power of its own. Space operations are an order of magnitude less ambitious from those of the generating satellites, as only the reflector is in space (geosynchronous orbit).

Relay Systems for transmission of power are treated in this appendix to emphasize their basic difference from generating systems such as the SPS. At this time, a pure transmission system is considered of lower priority than a system that generates electrical power. Also, preliminary economic analyses are not very favorable toward the competitiveness of the PRS.

In addition to the ground to ground relay mentioned above a recent suggestion is to place the generating satellite in a sun synchronous, low Earth orbit with an active relay satellite in geosynchronous orbit to transpond the power to the desired ground station. This mixture is discussed in Appendix 2.

Two critical areas have been identified for the Power Relay Satellite. The discussion below describes the areas and discusses the necessary efforts to resolve them. This should not be interpreted as a position favoring their immediate implementation.

Critical Areas for Relay

A. Reflectors for Passive Relay

Criticality

The heart of a Power Relay System is the passive reflector stationed in geosynchronous orbit. Preliminary efforts have defined it to be 1 km in diameter with a mechanical surface tolerance of ~ 1 mm RMS (electrical phasing is not possible). In addition the mechanical pointing and stabilization required is on the order of 1 second of arc. These requirements are not achievable with today's technology, nor will foreseen technology developments attain them.

Objectives of Required Efforts

1. Define surface control requirements.
2. Define attitude control requirements.
3. Perform a conceptual design to meet the requirements. Analyze the errors.
4. Define a test and demonstration program.

Recommended Approach

1. Do nothing until the economic competitiveness of the concept is better understood and a decision is made to pursue this option.
2. Perform a feasibility study/conceptual design to meet objectives 1-3.
3. Follow the study with system analysis encompassing trade-offs, integration, and the preparation of a development plan for a test and demonstration program.
4. Perform the terrestrial part of the test and demonstration program.

Preliminary Program Estimates

- Cost and Schedule (see chart)
- Capabilities and Experience
 - NASA-none direct (large space structures-indirect)
 - Rockwell International - performed the original analyses
 - Grumman - indirect, structural
 - Martin Marietta Corp. - indirect, structural
 - Raytheon Co. - indirect, microwaves
 - Many - indirect, large space structures.

REFLECTORS FOR PASSIVE RELAY (App. 1.A)

Preliminary Program Estimates

Cost and Schedule

TASK	FY	1	2	3
Feasibility study/conceptual design		\$50-75K ↔		
System analysis/trade offs/ integration/development plan			← \$500K →	
Terrestrial test and demonstration				← Several \$M

B. Power Relay Economics

Criticality

Preliminary analyses do not appear favorable with respect to economic competitiveness with alternative systems. Much has been said about the potential cost savings of being able to locate generation plants far from populated areas, but little has been substantiated.

Objectives of Required Efforts

1. Determine costs of PRS transmission from generator output to distribution bus bar.
2. Determine costs of alternative transmission systems.
3. Perform comparison of PRS with alternative systems.
4. Determine costs (and cost savings) of remote-sited generation plants.
5. Perform comparison of PRS (coupled with remotely sited generator) with alternate power generation systems (terrestrial and orbital).

Recommended Approach

1. Complete applicable, present studies (ECON and JPL).
2. Thorough inhouse study and decision prior to proceeding to any follow on efforts.

Preliminary Program Estimates

- Cost and Schedule - nothing new required

ECON study for MSFC will be complete by December 1975.

JPL study will have necessary data by December 1975.

Inhouse (Satellite Power Team) assessment of potential should be performed in the first quarter of CY76.

- Applicable Efforts

ECON/MSFC study and JPL study should fulfill first three objectives.

APPENDIX 2 - AREAS FOR FUTURE CONSIDERATION

During the preparation of this report additional areas with the potential of requiring treatment as critical areas surfaced. At present they are either part of another area(s) and/or are not well enough defined at this time for the depth of treatment required here. They will be considered by the Satellite Power Team (along with others that will inevitably come up as we proceed) after preparation of the Program Plan.

- Unit Quantities. The large scale of a satellite power system involves huge quantities of many individual devices. What special problems are involved in the manufacturing of the devices, the materials availability, and the energy consumed in the processes involved? At present this is treated individually in the separate areas. Possibly this may be a large enough problem, with sufficient commonality in all areas, to be treated separately. This question will be considered at the next critical area update.
- Sunsynchronous Generation/Geosynchronous Relay. This is a fairly recent concept that involves having the satellite generation portion in sunsynchronous orbit and a much smaller relay (probably active) satellite in geosynchronous orbit. The economics and competitiveness of this system are largely unknown. If they appear attractive after a preliminary study then elements of this system would be considered along with the others. After a preliminary look by the Satellite Power Team, a six months, \$50K, preliminary study might be in order to define the advantages and disadvantages of such a system.
- Short Circuit Protection. The occurrence of a short circuit at unpredictable bus locations on the SPS could lead to instantaneous destruction of the SPS or major parts of it. Present AC circuit breakers take between 6 and 10 cycles (about 0.1 second) for actuation. Whatever the actuating time is, the forces released by 60 to 100 KA are in the order of 10^{10} pounds or so. There are many potential causes of short circuits on the SPS like meteorites, space debris, assembly and maintenance errors and others. The SPS as a multi-gigawatt, high power generator with bus bar currents possibly in the 50 to 100 KA range, built from ultra-lightweight structures,

with high voltages present capable of delivering high power under assembly conditions, is particularly vulnerable to accidental short circuits that can destroy large parts of the SPS practically instantaneously.

In conventional power generation, transformation, transmission and delivery systems a "Short Circuit Study" for that particular system is one of the first and highest priority tasks.

- Satellite Nuclear Power Generation. The role of nuclear power from space eventually should be considered for both central power generation and as an interim power source for subscale demonstrations. At present our resources prevent any indepth analysis, so this has been postponed for later consideration.
- Regulatory Bodies. Interfaces and interactions with and between the national (and international) regulatory bodies that will be required of the SPS will be an extremely complicated task. These bodies will probably include Federal Power Commission, Federal Energy Office, Federal Communications Commission, Office of Telecommunication Policy, and many others.

APPENDIX 3 - ACRONYMS

AC - Alternating Current
AM - Amplitude Modulation
ARC - Ames Research Center (NASA)
CW - Continuous Wave
DC - Direct Current
EPRI - Electric Power Research Institute
ERDA - Energy Research and Development Administration
FRUSA - Flexible Rolled Up Solar Array
GSFC - Goddard Space Flight Center (NASA)
GSO - Geo Synchronous Orbit
HLLV - Heavy Lift Launch Vehicle
JPL - Jet Propulsion Laboratory
JSC - Johnson Space Center (NASA)
KSC - Kennedy Space Center (NASA)
LaRC - Langley Research Center (NASA)
LEO - Low Earth Orbit
LeRC - Lewis Research Center (NASA)
MHD - Magneto Hydro Dynamics
MSFC - Marshall Space Flight Center (NASA)
NASA - National Aeronautics and Space Administration
NSF - National Science Foundation
PM - Phase Modulation
R&D - Research and Development
RF - Radio Frequency
RFI - Radio Frequency Interference
SNR - Signal to Noise Ratio
SPS - Satellite Power System(s)
TWT - Traveling Wave Tube
UV - Ultra Violet
VSWR - Voltage Standing Wave Ratio